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by

Thomas F. Gross, Julie Amft, and Albert J. Williams 3rd

November 1993

Technical Report

Funding was provided by the Office of Naval Research under Grant Nos. N00014-89-J-1058 and N00014-90-J-1046.

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George V. Frisk

George V. Frisk, Chair
Applied Ocean Physics and Engineering

Data Report: Stress Measurements in the Bottom Boundary Layer with BASS Tripods STRESS II 1990-91

Thomas F. Gross†

Julie Amft†

A. J. Williams III††

Overview

The Sediment Transport Events on Shelves and Slopes experiment of winter 1990-91, STRESS II, was designed to provide a description of the physical conditions when sediment is in motion. Off the Northern California coast swell from off shore storms dominates the physics in the turbulent bottom boundary layer. The effects of waves on sediment transport at depths of 120m and 90m, where most surface wind chop is absent, was studied by measuring rapid motions within the bottom boundary layer across a wide range of time scales. This was accomplished this year by using in situ processing to compress most of the data and a very large data recorder to keep samples of raw data every few hours. The data presentation will emphasize the in situ processed data for an overview of the experimental results. A sample of the rapidly sampled raw data will also be presented.

The Benthic Acoustic Stress Sensor tripods, BASS, are bottom landing instrument platforms designed to measure the turbulent bottom boundary layers. The turbulent bottom boundary layer is the turbulent flow in the region from the sediment bed to 5 to 10 meters above the bottom. Within this region turbulent stress slows the flow from midwater column speeds to zero at the "no-slip" condition of the sea bed. Boundary shear stress scales sediment erosion rates and provides boundary friction which affects the full water column momentum balance. The stress is due to the mean boundary layer shear and enhanced by wave generated turbulence. Therefore measures of the mean profile and wave action are needed, as well as a modeling method by which the bed shear stress can be derived. The Grant, Madsen and Glenn models of wave-current interaction will be used for this.

The sheared velocity profile is to first order a logarithmic profile described by $U(z)=u_*/\kappa \ln z/z_o$. The shear velocity scale, u_*, describes the turbulence intensity and is used to derive the boundary shear stress $\tau_o=\rho u_*^2$. These quantities are measured by obtaining velocity profiles at half hourly intervals through the bottom 5 meters of the flow.

The wave action is derived by obtaining pressure power spectra every half hour. From this a peak frequency and pressure variance are obtained. By

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using linear wave theory these are related to the near bed wave velocity and excursion amplitude. The validity of these conversions are checked by comparison to velocity variance which is dominated by wave motions.

The BASS tripods provide turbulent bottom boundary layer descriptions by measuring the velocity at six fixed locations within 5 meters of the bed. The mean velocity data is used to derive logarithmic profile estimates of u_*. In addition the BASS velocity data, which is sampled at 1.6 Hz, can provide estimates of kinetic energy and the Reynolds stress tensor by averaging velocity component cross correlations:

$$<u'_i u'_j> = \frac{1}{30min} \sum_{t=0}^{30min} U_i(t) U_j(t) dt \ - \ \overline{U}_i \overline{U}_j$$

where $U_i(t)$ is the original time series data, $\overline{U}_i$ is the average over 30 minutes and u'_i is the turbulent velocity component.

Data Results

Two BASS tripods were deployed at the STRESS sites winter 1990-91. The first deployment did not yield usable data. The second deployment from Jan. 91 to March 91 yielded data at each site. The BASS tripods are named Bayshore 3, BS3, and Bayshore 4, BS4. BS3 was deployed to the shallower site in 90 meters and BS4 was deployed to the 130m site.

****

Bayshore III (BS3):
Depth: 90 meter site
Location: C3 38 37.88N 123 28.16W
Turn on : scan 1, 112 230, Jan. 12 2:30 GMT 1991 = 12.1042 year day
In water: scan 4, 112 400, Jan. 12 4:00 GMT 1991 = 12.1667 (y.d.)
Out water: scan 2673, 308 1830, Mar. 8 18:30 GMT 1991 = 67.7708 (y.d.)
Dock Zeros: scans 2692:2696, Mar. 9 4:00-6:00
Turn off: scan 2737, 310 230, Mar. 10 2:30 GMT 1991 = 69.1042 (y.d.)

Sensor	Height	Comments (Marku's notes)
Metal Clad #1	21 cm	all thermistors measured from
Metal Clad #2	110 cm	center of sensing element
Metal Clad #3	177 cm	
Metal Clad #4	264 cm	
Metal Clad #5	378 cm	
Metal Clad #6	450 cm	
Metal Clad #7	516 cm	
Metal Clad #8	585 cm	
BASS Pod 1	40.0 cm	Measure to approx. center of sensing
BASS Pod 2	76.0 cm	volume (see other side)
BASS Pod 3	135.0 cm	All six pods are large size sensor cages
BASS Pod 4	196 cm	Bottom of pod one is 23.5 cm off deck
BASS Pod 5	257 cm	Guys from above six, four and two.
BASS Pod 6	493 cm	Guy from below one.

Transmissometers

Tr 1	138 cm	10cm path length
Tr 2	342 cm	15 cm path length
Pressure	394 cm	NJ1 or #9129

Camera No camera on BS3. Relying on Wheatcroft's SCAT, 80 cm.a.b.

Compass: 6e grey code, = 84 degrees
Bayshore III AC to compass angle -75 or 255???
339 deg N = 84+255 = Direction of flow FROM 339N is positive AC axis
Magnetic declination 16.5.
Rotate AC to East, BD to North with 90-21+16.5 cclkw

Compass: 6e grey code, = 84 degrees.
Magnetic declination 16.5.

Bayshore III AC to compass angle +15
Rotate AC to East and BD to North with -90
Total rotation: 84 +16.5 -90 +15 = 25.5 cclkw

****

BayShore IV (BS4):
Depth:
Location: C4 38 35.55N 123 32.23W
Turn on : scan 1, 108 2330, Jan. 8 23:30 GMT 1991 = ? year day
In water: scan 9, 109 330, Jan. 9 3:30 GMT 1991 = ? (y.d.)
Out water: s 2992, 312 700, Mar. 12 7:00 GMT 1991 = ? (y.d.)
Dock Zeros: scan 3057:3061, Mar. 13 15:30-1730
(best zero) scan 3058, Mar. 13 16:00
Turn off: scan 3061, 313 1730, Mar. 13, 17:30 GMT 1991 = ? (y.d.)

Sensor	Height	Comments
Metal Clad #1	17 cm	all thermistors measured from
Metal Clad #2	103 cm	center of sensing element
Metal Clad #3	195 cm	
Metal Clad #4	295 cm	
Metal Clad #5	379 cm	
Metal Clad #6	455 cm	
Metal Clad #7	520 cm	
Metal Clad #8	598 cm	
BASS Pod 1	37.5 cm	Measure to approx. center of sensing
BASS Pod 2	74.5 cm	volume (see other side)
BASS Pod 3	135.0 cm	All six sensor cages are large size
BASS Pod 4	194 cm	
BASS Pod 5	254 cm	Bottom of cage 1 is 22.6 cm off deck
BASS Pod 6	495 cm	Support ring is 5.05 cm thick (2inch)

Guy rings are inserted at each point where guys are.

Transmissometers

Tr 1	139 cm	5 cm path length
Tr 2	340 cm	5 cm path length

Pressure 400 cm NJ 2 or #13032

Camera 319 cm Measure from lens of camera (not case)
28mm lens with index of refraction = 34mm

Compass: 28 grey code, = 284 degrees
Magnetic declination 16.5.
Bayshore IV AC to compass angle +75
Rotate AC to East and BD to North with -90
Total rotation: 284 +16.5 -90 +75 = 285.5 cclkw

Footpad is standing on a bolt of 1 cm height. Footpad is 3.7cm thick.

All measurements are to the dock.

****

Data recorded on each tape:

A more complicated data recording scheme was used in the STRESS II experiment than STRESS I of 1988-89 (Gross and Williams 1988-89 Datareport). The data are received from the BASS serial UART by a Tattletale VI with a 20 Megabyte hard drive. BASS is programmed to deliver simple "Event" records at 2.0 Hz. Every half hour the "Average" records created by the program in BASS are transmitted. The Tattletale receives the BASS data and does some additional calculations as well as storing the data. The Tattletale writes all data to its 296K RAM "datafile". Every 21 hours the datafile is written to the hard disk. The main part of the data consists of two records of FFT data and the "average" record written each half hour. Two minute averages of the velocity at every level are formed in the Tattletale and written to disk. The FFT calculations use part of the datafile as scratch to hold the four * 512 length time series. These are recorded when the datafile is written. In addition each half hour eight minutes of raw "event" records are recorded to the datafile. Therefore the eight minutes in memory are recorded each 21.5 hours when a data file is written. The datafile is logically subdivided into seven banks:
DATA BANKS

0-7FFF
BANK 1
AVERAGEs and FFTs
248 bytes per average record from BASS
520 bytes per FFTs generated in TOPSTRES.TTB
42*(248+520) = 32256 = 7E00
Therefore the cycle for writing to disk is now 21 hours.

8000-FFFF
BANK 2
TWOMINS: Two minute averages of horizontal velocity components of each pod.

10000-17FFF
BANK 3
Room kept around for the directional wave spectra
(Still needs some work)

18000-1FFFF
BANK 4 FFT storage
P,U3,V3,U6,V6
20000-27FFF
BANK 5 FFT storage
W1,W2,W3,W4

28000-2FFFF, 30000-37FFF

BANK 6 AND 7
Event records from first 8 minutes of each half hour
****

The 248 byte average record from BASS is as follows:

AA B3(4) M(onth)D(ay) H(our) M(inute) -

24 2-byte word values for mean values of velocity:
4 per sensor   A - D on each sensor
6 sensors   Sensor 1 is at the bottom
Values approx.= 8000H (2 bytes) V=0 cm/s

Values approx.=	8000H (2 bytes)	V=0 cm/s
	9000	>0 velocity
	7000	<0 velocity
	FFFE	FS=120 cm/s
	0001	FSneg = -120 cm/s

ffff is reserved to represent failures

6 bytes (quality word - all zeros if nothing blocks the ACM sensors).
It is an error counter. It is 2 bits/axis
00 no error
01 1-15 errors
10 16-63 errors
11 >64 errors
Start left to right from the bottom.

Cross Products
10 words/sensor (1 word = 2 bytes)
4 X 4 matrix:

```
AA AB AC AD
   BB BC BD
      CC CD
         DD
```

Done for sensors: 2, 3, 4, 5
Total of 40 - 2 byte words
Typical value close to 0000 (e.g. 0030)
They are a measure of turbulent kinetic energy.

Next 30 bytes = 2 min. over-ranged velocity for pod 3 (middle pod).
(A 2-byte number is represented by a byte from the middle.
Thus a speed of 8030h would be recorded as 03.)
U, V, U, V ...

Analog Values (repeat 3 times; read each 10 mins.)
TEMPERATURE, TRANSMISSOMETER, PITCH & ROLL
TEMP (2 byte words for each thermistor; 8 thermistors)
FFFF (FS) 32 deg C

0000 (0S) 0 deg C
Read from bottom up.
More offset between thermistors than change.

2 byte word = Lower Transmissometer
2 byte word Upper Transmissometer
Values 0000H = Beam blocked
FFFF = Absolutely transparent water (no water is that transparent)
C000 = is a typical value (3/4 FS)
2 bytes Pitch (This shouldn't change)
2 bytes Roll (This shouldn't change)
4000 = is typical number (or 6000)

FFT RECORD
Fourier transformations of pressure variance, frequencies (1:40)/256s.
Fourier transformations of velocity variance, frequencies (1:40)/256s.

Calibrations:

BASS velocities

BASS velocity calibrations involve a gain factor and a zero offset. The gain factor is only a function of the path length and speed of sound in water, neither of which are variable, gain = 0.00368 cm/sec /bit. The zero offsets are due to capacitence variations of the cables. This changes slightly with each configuration of the tripod. Therefore zero velocities are measured by deploying the tripod with each pod wrapped in plastic to still the flow. These zero deployments were done off the dock on March 9 and 13 after the experiment. The maximum magnitudes of the zero velocities are ~5 cm/s. One channel from each pod may be discarded. A large offset zero is an indicator of trouble and is usually the channel which is discarded. Further refinements of the zeros are calculated by assuming a directional dependence of errors (another tech. report). By using these zeros, velocity vectors are obtained which yield logarithmic profile slope with regression coefficients in excess of 0.98 indicating confidence of better than 0.2 cm/s in the mean speed estimates.

Table 1

BS3 Zeros (cm/sec) scan 2693, March 9, 4:30 GMT

channel \ pod #	1	2	3	4	5	6
A	0.5814	1.2475	-0.4306	-1.1482	0.4490	4.3718
B	0.5226	1.1739	-1.6486	0.7949	-1.1923	-
C	1.1371	1.0120	-0.5226	-0.5778	1.6597	-
D	-0.8758	0.9053	-0.1398	0.3680	0.2760	2.9146

BS4 Zeros (cm/sec) scan 3060, March 13, 17:00 GMT

channel \ pod #	1	2	3	4	5	6
A	4.4086	-1.9798	0.1914	2.0166	0.5152	-0.5630
B	6.6203	-0.0699	3.6616	2.4325	0.5189	-0.2981
C	-0.0405	1.6891	0.3533	4.2320	-0.5594	1.1813
D	-0.8170	0.1251	-1.0120	3.2605	-0.7618	1.1334

Figure 1 shows a few sample profiles. The four symbols for each level represent speed estimates based on three axes, giving four combinations. The quality of the zero calibrations is visually represented by the consistency between estimates of speed.

Transmissometers

The transmissometers directly measure percent transmission, %Tr = 100%*bits/32768. Light attenuation, $\alpha = m^{-1}$, is derived from:

$$Tr = Tr_o e^{-\alpha l}$$

$$\alpha = \frac{1}{l}\log\frac{Tr_o}{Tr}$$

where l is the path length of the light beam and Tr_o is a calibration transmission at zero light attenuation. Tr_o is due to clear water attenuation and an unknown effect from plastic spacers we used to reduce the pathlength from 25 cm to 10 cm. Their attenuation effect has not yet been calibrated. But attenuation is simply offset a constant amount by Tr_o. The preliminary plots use Tr_o=100% Therefore when the transmissometers were working the measures of light attenuation can be seen to go from a minimum of ~4 m^{-1} which is the offset due to Tr_o to maximum values of 30 m^{-1} which represent light attenuation of at least 26 m^{-1}.

Thermistors

Thermistors will be properly calibrated later this Fall. A rough calibration has been applied:

$$T = 25*bits/65535$$

where bits ranges 0 to 65535 corresponding to 0 to 25 degrees Centigrade.

Tilt and Roll Sensors

The tilt and roll sensors output a 0 to 2 Volt signal cooresponding to angles of -45° to +45° . The A/D convertor maps 0 to 5 Volts to 0 to FFFFh. The formula for angles in degrees from the tilt or roll word, W, is:

$$\Theta° = (W \times \frac{5V}{65535} - 1V) \times \frac{45°}{1V}$$

The resolution is 0.0034° per bit or 0.34° per 100 bits. Zero degrees is W = 13107 = 3333h. Because the STRESS matrix is expressed in streamline coordinates and the horizontal to the slope of the sea bed is not actually known to within 1/200, the tilt and roll are used to check that the angles are less than 0.3° = $\tan^{-1}1/200$.
This is equivalent to 13000<W<13200. BS3 has Tilt = -0.522°, Roll = +0.903°. BS4 has large angles: Tilt = -2.86°, Roll = -3.48°.

Pressure and Pressure FFT Calibrations

The Paroscientific pressure sensors return a pulse at a rate proportional to the pressure. The BASS electronics samples this rate and records the number of pulses in some time interval. Because the BASS are actually sampling at 8 Hz and averaging down to 2 Hz the time interval for the the count is .125 second even though it is written down at 2 Hz. The number is also shifted by a factor of 32 (I don't know why). The ParoScientific pressure signal count is given as a 3 byte number, C. The count is converted into a period, T, by inverting the frequency found by the product of count and sampling rate (0.125 sec):

$$T = \frac{0.125 \text{ sec}}{C/32} \times 10^6 \mu s/\text{sec} \qquad \textit{microseconds}$$

Matlab:
T= 0.125 ./(C/32) *1000000
The pressure is given by the equation:

$$P = A(1-T_o/T) - B(1-T_o/T)^2$$

Matlab:

P=A*(1-To ./T) - B*(1-To ./T).^2

Where A, B and T_o are calibration coefficients; Paro #13032: A=3192.40 psia, B=1592.42 psia, To=26.28868 μs. Paro #9129: A=3181.1510 psia, B=1574.621 psia, To=26.47018 μs. The conversion of PSIA to meters of salt is achieved with: 68.947 millibar = 1. psi; 1 millibar = $(1.0197)^{-1}$ cm water or 1 millibar = $(1.0197*1.02813)^{-1}$ cm standard salt water; 1 atmosphere = 1013.3 millibar. So:

$$p = (P*68.947-1013.3)/(1.02813*1.0197) \qquad cm$$

Matlab:

p=(P* 68.947 - 1013.3) / (1.02813 * 1.0197)

A few pressure numbers in counts from BS3 (Paro # 9129) where the depth should be approximately 85 meters are 144270, 144300, 144350 decimal. These numbers give 82.955, 82.558, 81.896 meters. The slope of the curve is -76.0 bits/meter salt water. A few pressure numbers in counts from BS4 (Paro # 13032) where the depth should be approximately 120 meters are 142500, 142525, 142550 decimal. These numbers give 119.36, 119.04, 118.72 meters. The slope of the curve is -77.4 bits/meter salt water. Uncertainity in this calibration is due to my most recent calibration factors for the pressure sensors being from 1982.

The Fourier transform of the pressure signal is calibrated with conversions of measured bits to meters of salt water and the various scaling factors contained in the Fourier transform and its gain adjustments. Ultimately the summation over the components of a Fourier transform give the variance of the signal:

$$\sigma_P^2 = \frac{1}{2\pi} \sum_{freq=0}^{freq=1} \tilde{P}^2$$

Where $\tilde{P}^2$ are the squared magnitudes of the pressure spectra. These are written to tape in minimal form and are called "$fftbits^2$". The gain and FFT calibrations reduce to:

$$\sigma_P^2(bits) = \frac{1}{2\pi} \sum_{freq} fftbits^2/20$$

Although the full calibration for ParoScientific pressure sensors is nonlinear the range of fluctuations about the mean depth is quite linear. The slope is very near -77 bits/meter salt water. The full calibration conversion is

$$\sigma_P^2(meters^2) = \frac{1}{2\pi} \sum_{freq} (fftbits/77bits/meter)^2/20$$

Derived quantities:

The four components of the velocity vector measured by a BASS pod are rotated into three component Cartesian velocity vectors:

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = A * \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix}$$

where A is the rotation matrix which takes the four components of a BASS pod into the three Cartesian components. A may be defined five ways. Four matrices are based on combinations of just three axes at a time. The fifth is the average of the other four methods:

$$A_5 = \frac{-1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 \\ 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix}$$

Next we rotate from the pod's coordinate system to the coordinate system of the BASS electronics case which contains the compass, tilt and roll sensors. The velocity vector begins in coordinates with U aligned with the A-C axis. Regrettably the geometry of the different BASS tripods makes the angle rotation differnent for almost every experiment and tripod. For example the angle of the A-C axis with the compass case for the BS3 tripod is 180° + 75°. BS3 requires $\theta_{AC} = 255°$. BS4 requires $\theta_{AC} = 345°$.

$$\begin{bmatrix} \cos\theta_{AC} & -\sin\theta_{AC} & 0 \\ +\sin\theta_{AC} & \cos\theta_{AC} & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} U \\ V \\ W \end{bmatrix}_{pod} = \begin{bmatrix} U \\ V \\ W \end{bmatrix}_{case}$$

This produces vectors with U component magnitude equal to the flow parallel to the BASS electronics case.

Now the frame tilt, θ_t, and roll, θ_r are removed by rotating about the Y axis and then the X axis to yield a coordinate system flat with the sea bed (assuming gravity is perpendicular to sea bed):

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_r & -\sin\theta_r \\ 0 & +\sin\theta_r & \cos\theta_r \end{bmatrix} \times \begin{bmatrix} \cos\theta_t & 0 & -\sin\theta_t \\ 0 & 1 & 0 \\ +\sin\theta_t & 0 & \cos\theta_t \end{bmatrix} \times \begin{bmatrix} U \\ V \\ W \end{bmatrix}_{case} = \begin{bmatrix} U \\ V \\ W \end{bmatrix}_{caseflat}$$

A rotation to put the $[U,V,W]_{caseflat}$ vector into a East, North, Up coordinate system is based on the compass reading. The compass is measured in the pressure case of the BASS. The compass angle measured for BS3 was 84°, i.e. the end of the case is pointed toward 84° N (magnetic). U will be turned into East so that is another 90°. Magnetic declination at the STRESS area is -16.5° in 1988-9. The total rotation is therefore θ_{EN} = 90° - 84° - 16.5° = -10.5°. This angle is the rotation of the $U_{caseflat}$ axis vector to east. (As opposed to a rotation of -10.5° of the caseflat coordinate system to East-North coordinate system. Note the sign of the sine terms in the matrix below). The rotation is around the Z axis:

$$\begin{bmatrix} \cos\theta_{EN} & -\sin\theta_{EN} & 0 \\ +\sin\theta_{EN} & \cos\theta_{EN} & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} U \\ V \\ W \end{bmatrix}_{caseflat} = \begin{bmatrix} East \\ North \\ Up \end{bmatrix}$$

The ten components of the cross correlations of the four axis of the BASS pod are rotated into the six unique components of the Reynolds stress tensor.

$$\begin{bmatrix} uu & uv & uw \\ uv & vv & vw \\ uw & vw & ww \end{bmatrix} = A * \begin{bmatrix} a'a' & b'a' & c'a' & d'a' \\ a'b' & b'b' & c'b' & d'b' \\ a'c' & b'c' & c'c' & d'c' \\ a'd' & b'd' & c'd' & d'd' \end{bmatrix} * A^T$$

Futher rotations are applied to put $u_i u_j$ into streamline coordinates.

Logarithmic profiles and wave current interactions

A least squares fit of the logarithmic velocity profile equation, $U(z) = u_* / \kappa \ln(z/z_o)$, yields the shear stress velocity scale, u_*, the roughness length scale, z_o, and the regression coefficient, R^2. Only the current meters below 2 meters were used as the velocity profile deviates from logarithmic above that level. The calculation was done for all the data. However when the mean velocity is low ($Ubar < 5cm/s$) the fit is nearly meaningless. In addition when wave action is large ($U_b > 10cm/s$), u_* and z_o must be interpreted with a wave current interaction model.

The surface pressure spectra are not monochromatic. Surface waves are usually the result of locally generated wind waves and swell. However, the pressure signal at the bed is attenuated at high frequency. Linear wave theory predicts that surface wave amplitude **a** at frequency ω is attenuated to a near-bed pressure response, p, by:

$$p = \frac{\rho g}{\cosh kh} \mathbf{a}$$

where ρ is density of water, g is gravitational acceleration, h is the depth and k is the wave number. Wave number is related to frequency for linear shallow water waves by $\omega^2 = gk \tanh kh$. In 90 meters depth the attenuation factor, $(100\%/coshkh)$ is 90% at 0.025 Hz, 35% at .066 Hz and 1% at 0.12 Hz. Therefore surface chop is not important to the bed stress, but swell waves in the range of 10 to 25 seconds will cause significant near-bed motions.

The integral velocity spectra was used to obtain near-bed velocity variance, $\sigma_{u_i}^2$.

$$\sigma_{u_i}^2 = \int \tilde{u}_i^2 \, df$$

The mean frequency was found from the velocity spectra, $\tilde{u}_i^2$, using:

$$\bar{F} = \frac{\int \tilde{u}_i^2 f \, df}{\int \tilde{u}_i^2 \, df}$$

This method was compared to one of choosing the frequency of the largest spectral peak and was found to give similar results. $\bar{F}$ is a robust measure because the wave spectra are relatively narrow.

Linear wave theory can be applied to solve for the near bed wave orbital velocity, u_b, near bed wave induced particle excursion distance, a_b, the surface wave amplitude, h, the near bottom pressure variance, σ_P (meters = P/ ρ g), given any one (u_b) and the wave frequency, f, obtained from the spectra.

$$k = 2\pi \frac{f}{\sqrt{g\,\delta}}$$

$$\omega = 2\pi f$$

$$U_b = 2\sigma_P \ \omega \frac{cosh(k\delta)}{sinh(k\delta)}$$

$$A_b = 2\sigma_P \ \frac{cosh(k\delta)}{sinh(k\delta)}$$

$$h = 2\sigma_P \ cosh(k\delta)$$

The wave velocity u_b will be the major contribution to the kinetic energy or the trace of the Reynolds stress tensor. If this is true then $q^2 = u'u' + v'v' + w'w' \approx \frac{1}{4} u_b^2$.

Wave current interaction models such as the Grant and Madsen model seek to establish a connection between boundary layer forcing parameters and the turbulent response. The forcing parameters are: wave frequency, $\bar{F}$, near-bed excursion amplitude, A_b, and a specified velocity at a level above the wave boundary layer but within the turbulent boundary layer, $U_r(58\ cm)$. The turbulent response parameters are: wave boundary layer velocity scale u_{*cw} and a mean current layer velocity scale, u_{*c}. The problem cannont be closed until a statement about the geometry of the bottom is added. This is usually the bed roughness parameter $z_o = k_b/30$. However the bed roughness may be solved for if information about the turbulent response has been measured.

The G&M model specifies a disjoint linear eddy diffusivity that uses u_{*cw} and u_{*c}. This results in a continuous, two part logarithmic profile of mean velocity. The slope of the inner part scales with u_{*c}^2/u_{*cw} and the bed roughness z_o. The slope of the outer part scales with u_{*c} and has an effective roughness z_{oc}, much larger than the physical roughness scale.

$$U(z) = \frac{u_{*c}}{\kappa} \frac{u_{*c}}{u_{*cw}} \ln \frac{z}{z_o} \qquad z < \delta_w$$

$$U(z) = \frac{u_{*c}}{\kappa} \ln \frac{z}{z_{oc}} \qquad z > \delta_w$$

The model results may then be compared to the least squares fit of the measured velocity to the outer logarithmic profile which yields somewhat independent estimates of u_{*c} and z_{oc}. Alternatively the model has been solved for u_{*c} and z_o by using the least squares estimate of z_{oc} as input. The close agreement of u_{*c} and the least squares u_* is never surprising. The model requires U_r to be given. At least 50% the variance of u_* and u_{*c} is attributable to variance of U_r.

The results of derived z_o are surprisingly good. Of course the method only works well when both waves and mean current are large, ($U_b > 10 cm/s$ and $\overline{U_r} > 5 cm/s$). During sediment transporting storms the bottom roughness can be seen to quickly decrease with large low frequency wave action and then rebuild slowly as the waves decrease in amplitude and period with the waning of the storm. The rebuilding of z_o is the formation of wave generated ripples and perhaps of biological reworking of the surface.

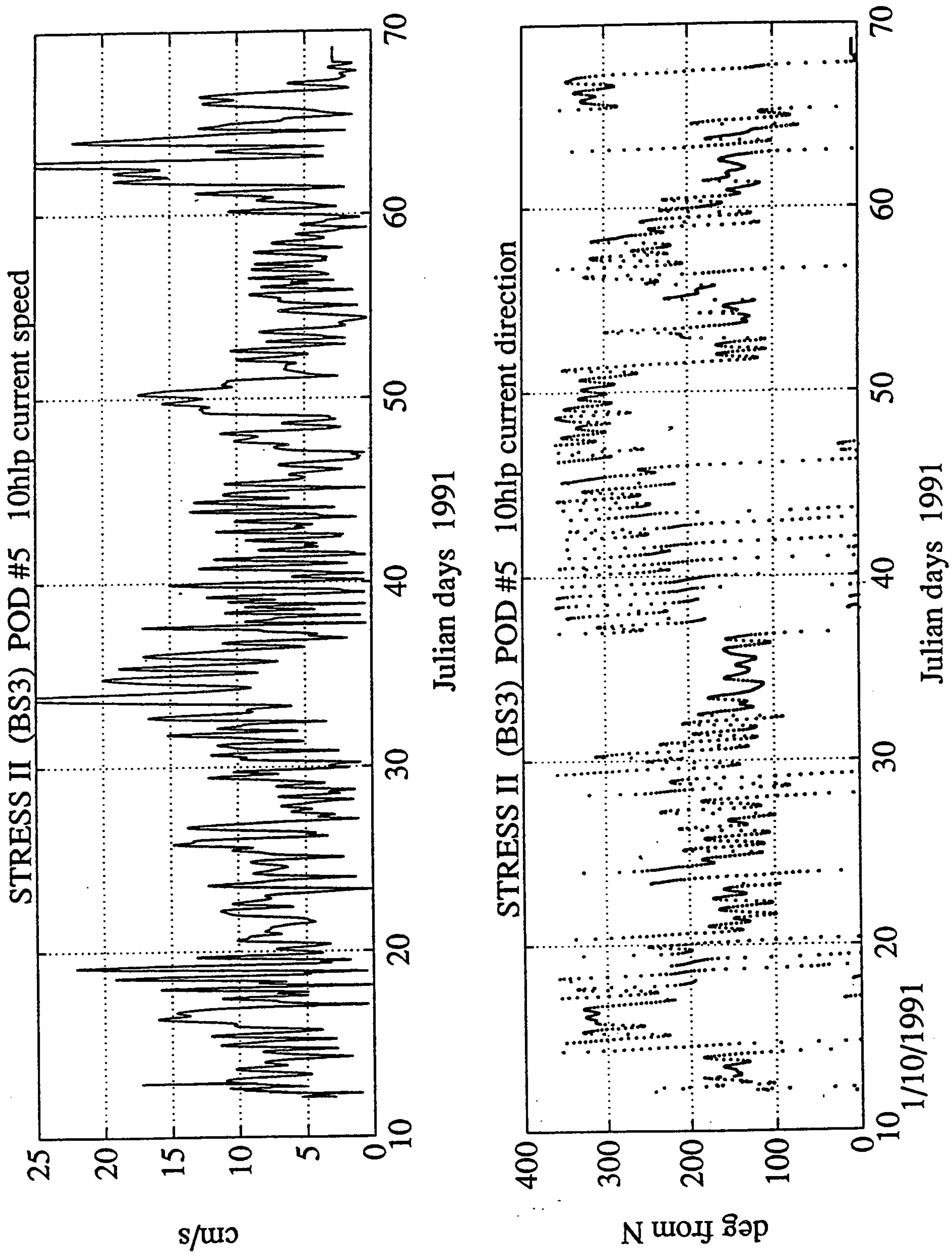


Fig. 1. Mean speed and direction for the fifth pod at 2.57 m.a.b. This data is 10 hour low passed.

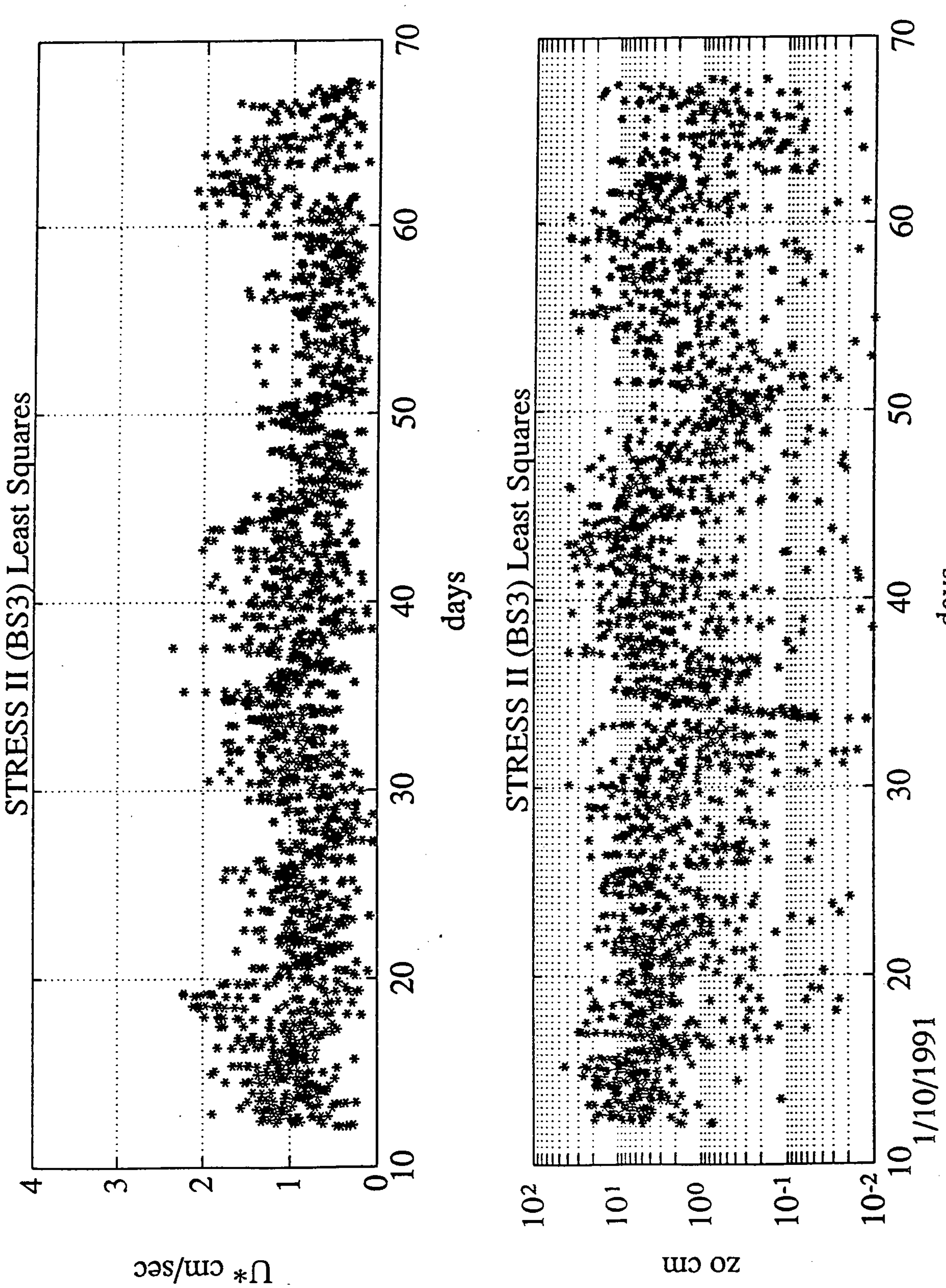


Fig. 2. Least squares estimates of the slope of the logarithmic velocity profile yield u_* and z_o. This plot shows only estimates for which R^2 is greater than 0.8.

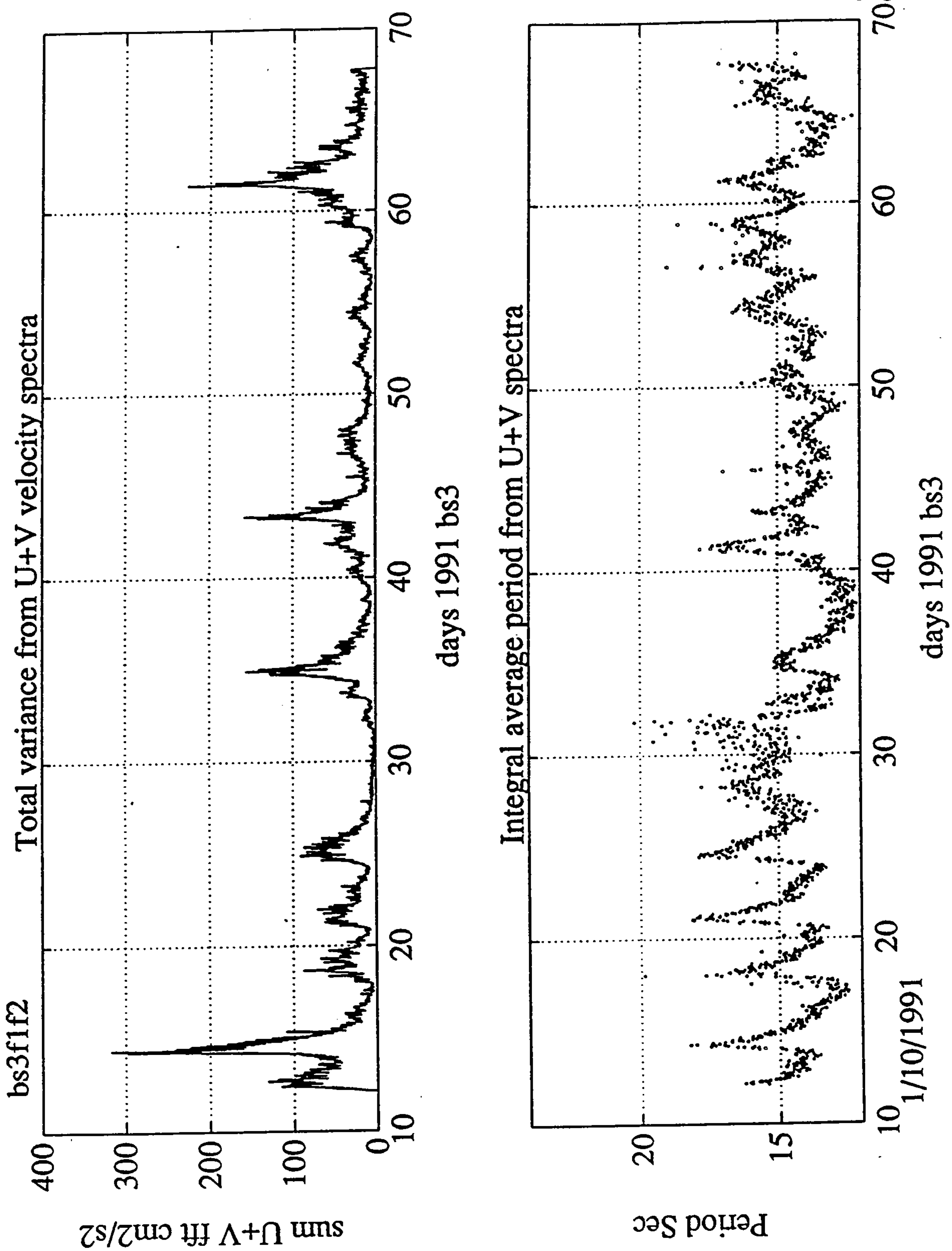
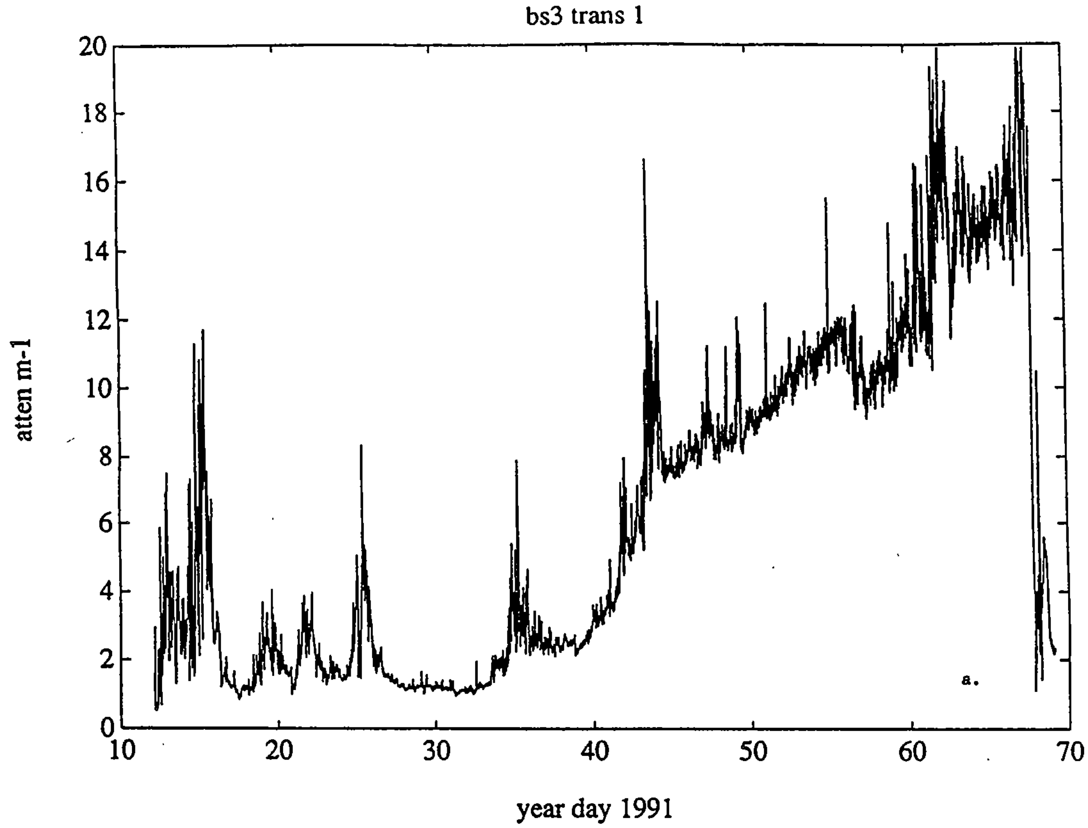


Fig. 3. Total velocity variance derived by summing the FFT estimates across frequencies 0.003255 to 0.1302 Hz. The period of the waves is estimated by spectral weighted averages of the frequency.



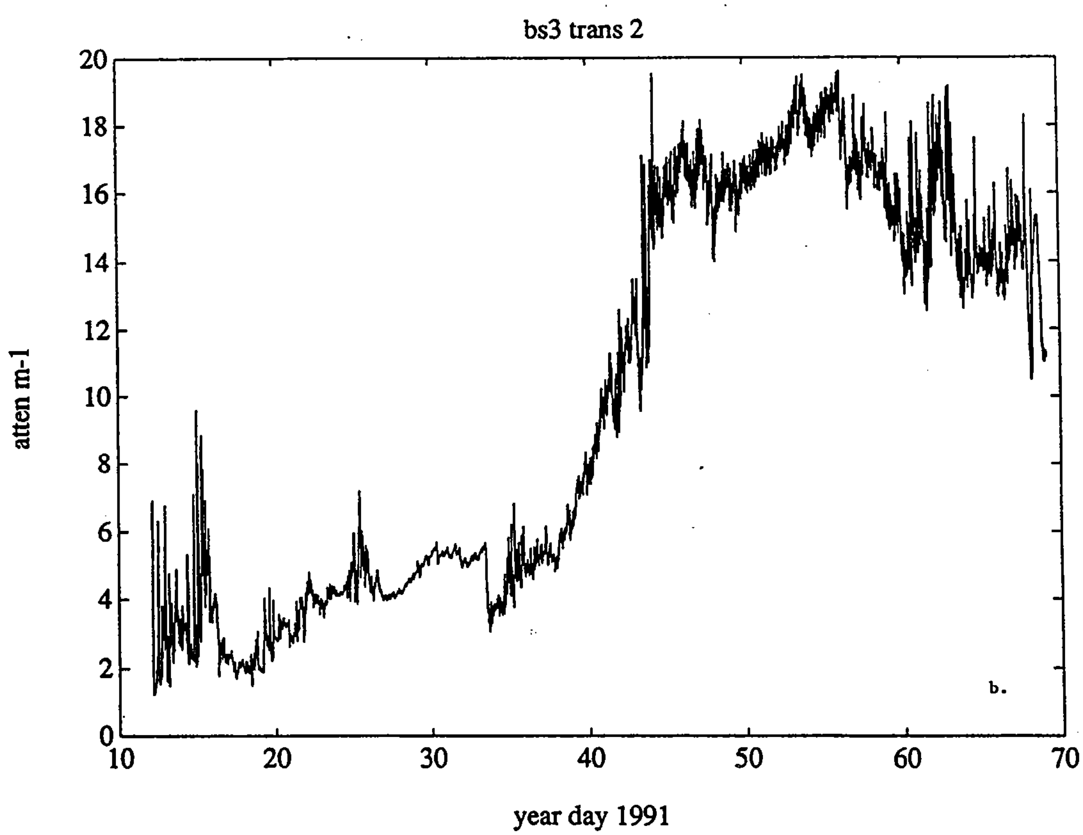


Fig. 4. Transmissometers 1(a) and 2(b). Considerable clouding or fouling of the transmissometers through the deployment is evident.

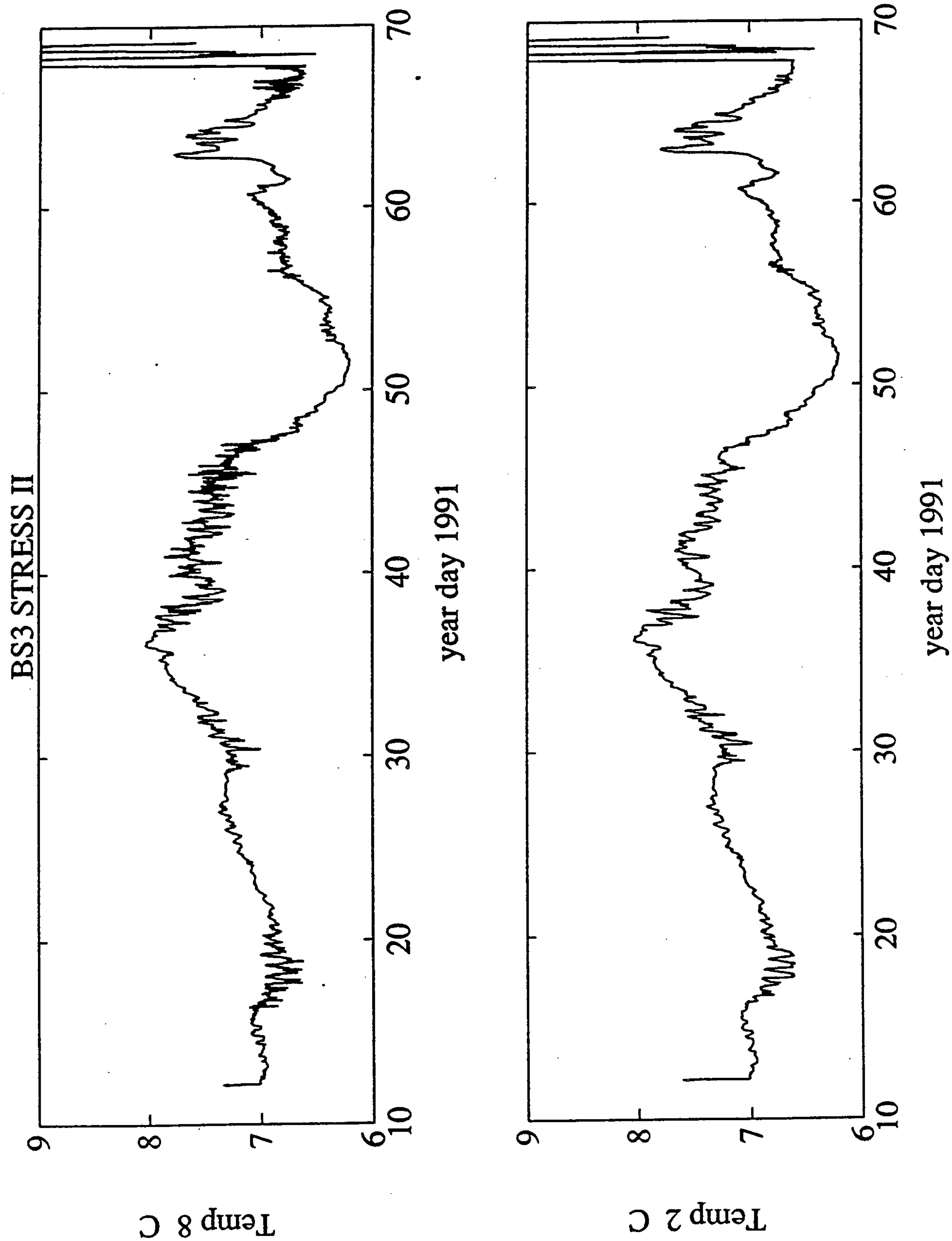
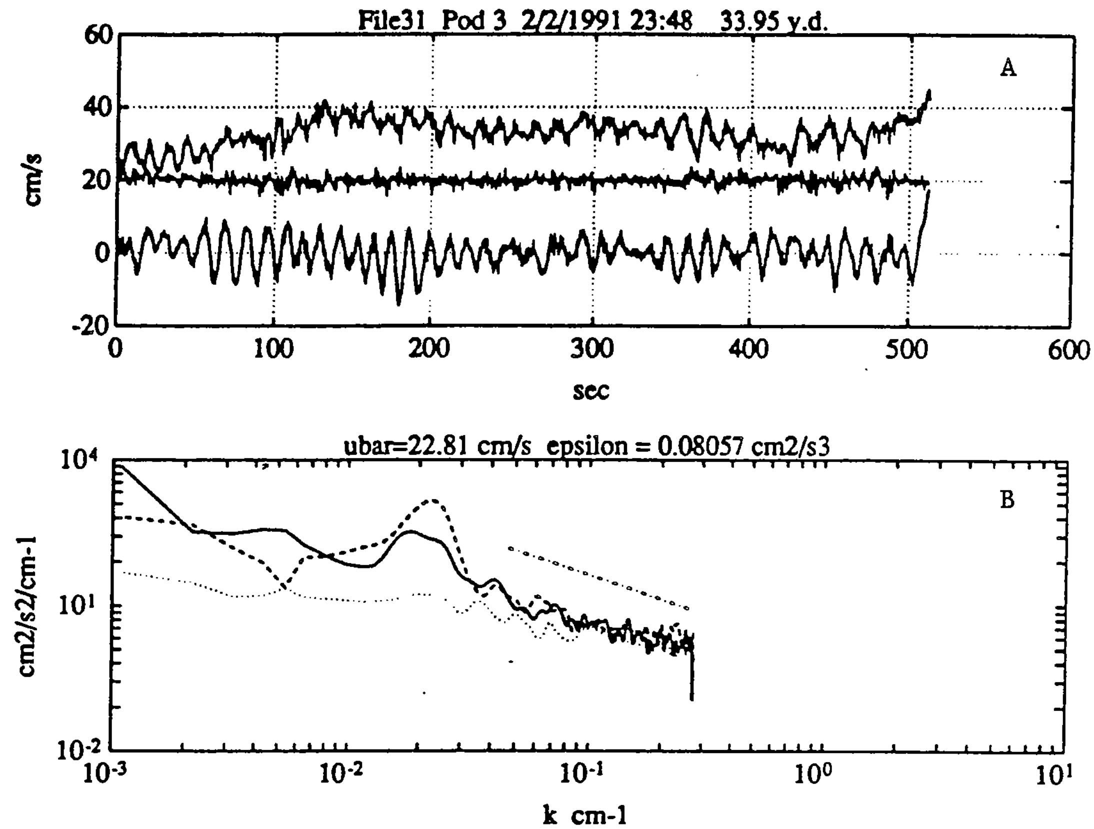
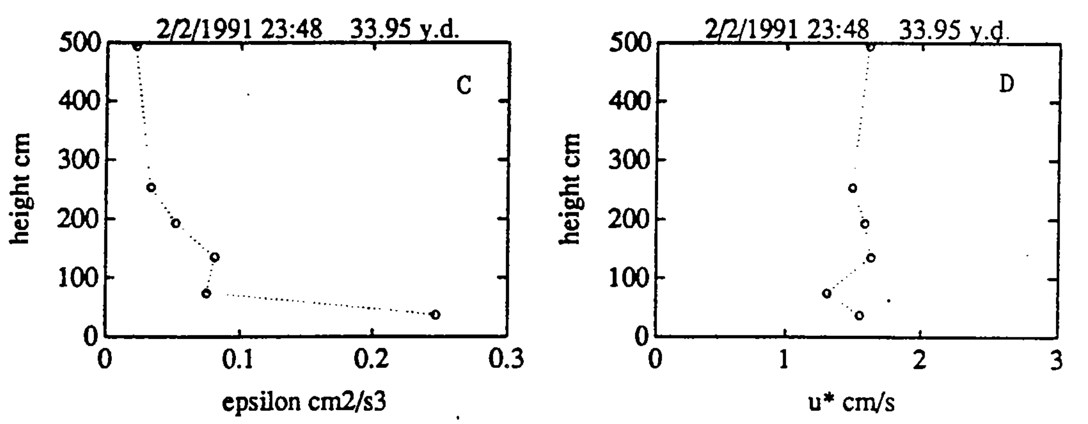


Fig. 5. Temperature records for the deployment. BS3 (90m depth) thermistors at position 8 (5.85 m.a.b.) and position 2 (1.10 m.a.b.).





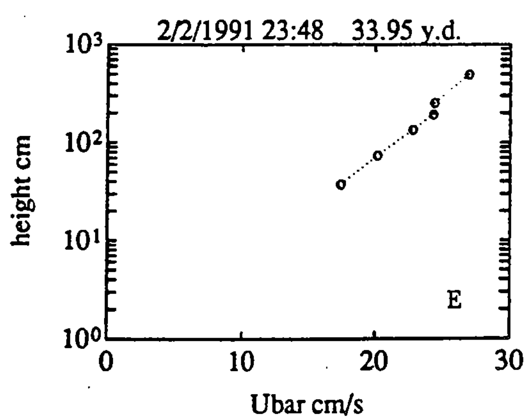


Fig. 6(*a-d*). Sample event data. Every 20 hours, 8 minutes of raw data is fully recorded. The instantaneous time series at all six levels allow a full spectral analysis. Plot *A*: Time series of *u, v, w* components (10 cm/sec offset between components). Plot *B*: Three component spectra with -5/3 reference line; *k* calculated as $2\pi f/\bar{U}$. Plot *C*: Dissipation estimates from spectra profiled with height. Plot D: u_* from $\varepsilon = u_*^3/\kappa z$. Plot *E*: Logarithmic profile of velocity.

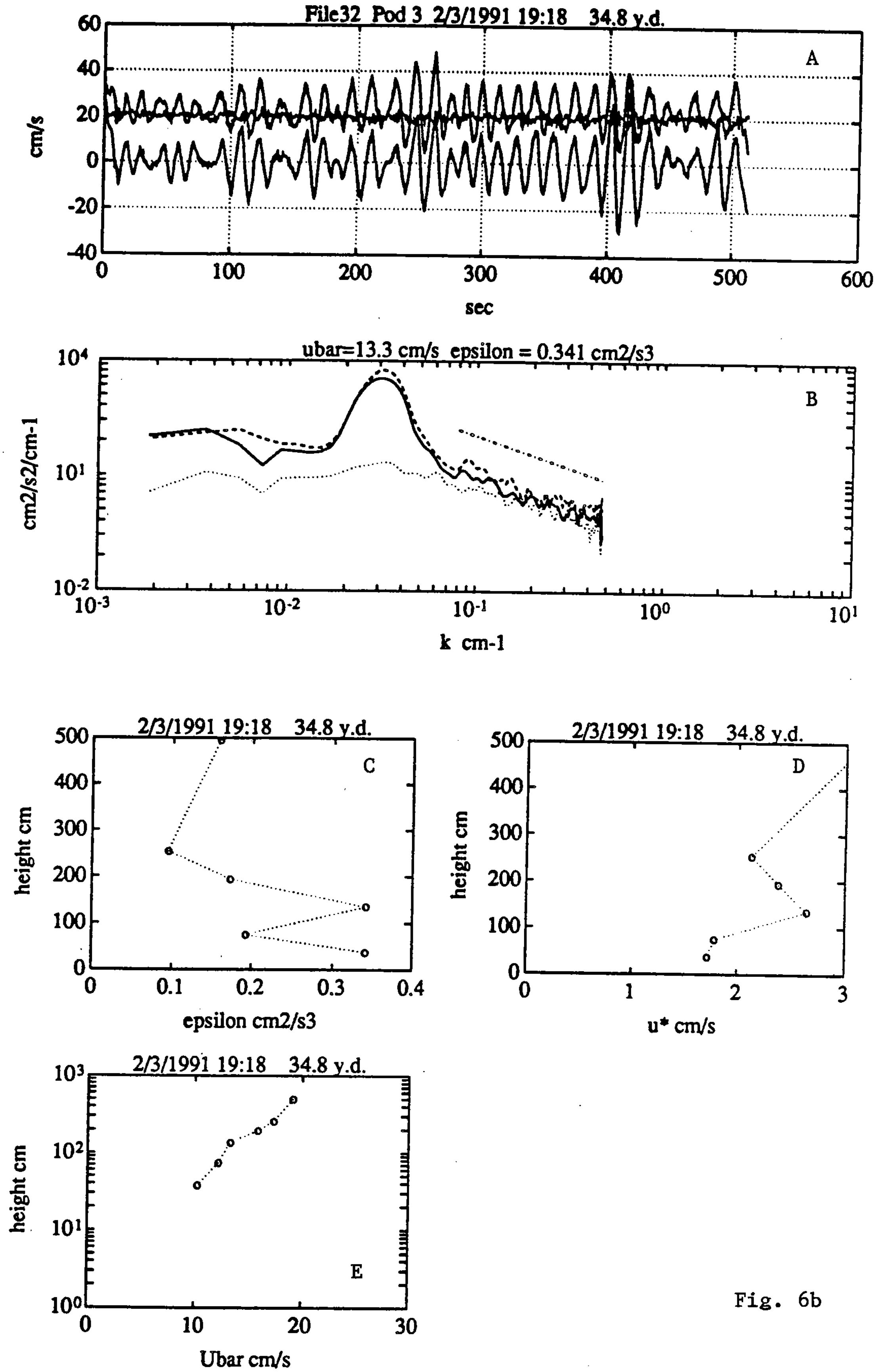
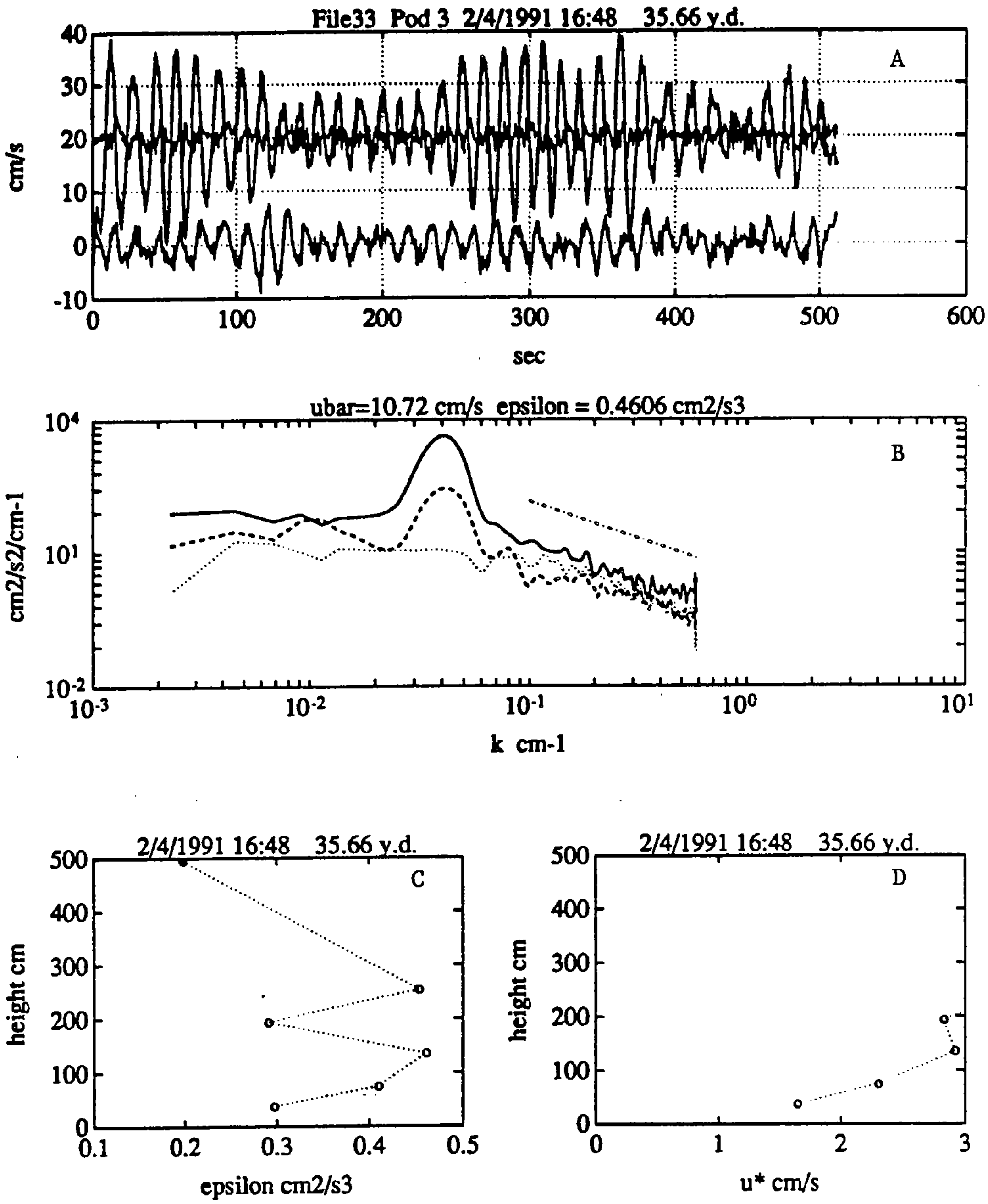
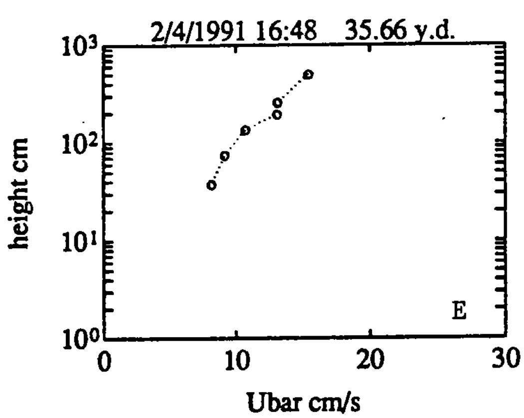

File32 Pod 3 2/3/1991 19:18 34.8 y.d.
A
cm/s
sec
ubar=13.3 cm/s epsilon = 0.341 cm2/s3
B
cm2/s2/cm-1
k cm-1
2/3/1991 19:18 34.8 y.d.
C
height cm
epsilon cm2/s3
2/3/1991 19:18 34.8 y.d.
D
height cm
u* cm/s
2/3/1991 19:18 34.8 y.d.
E
height cm
Ubar cm/s

Fig. 6b



File33 Pod 3 2/4/1991 16:48 35.66 y.d.
A
cm/s
sec
ubar=10.72 cm/s epsilon = 0.4606 cm2/s3
B
cm2/s2/cm-1
k cm-1
2/4/1991 16:48 35.66 y.d.
C
height cm
epsilon cm2/s3
2/4/1991 16:48 35.66 y.d.
D
height cm
u* cm/s



2/4/1991 16:48 35.66 y.d.
E
height cm
Ubar cm/s

Fig. 6c

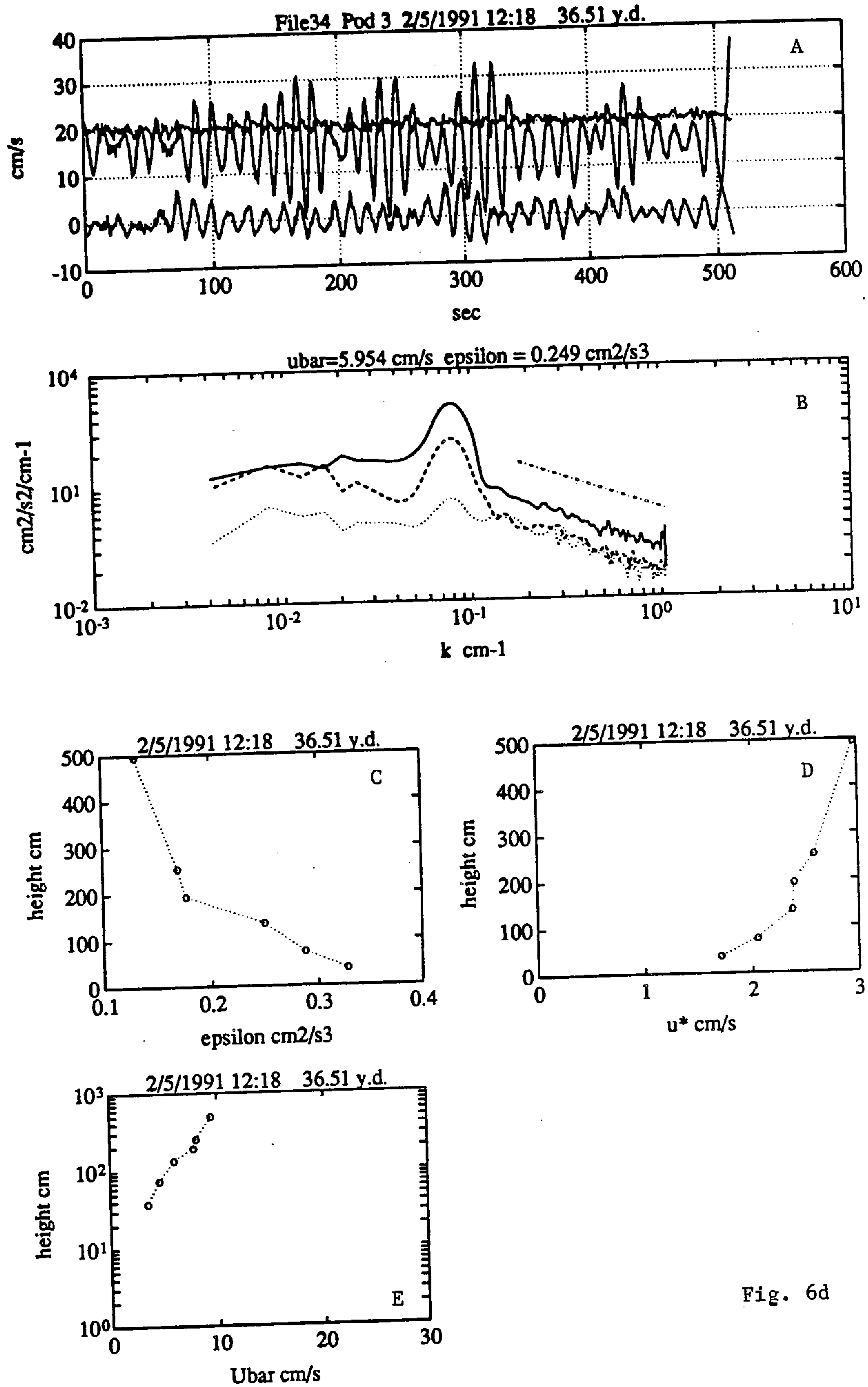

File34 Pod 3 2/5/1991 12:18 36.51 y.d.
A
cm/s
sec
ubar=5.954 cm/s epsilon = 0.249 cm2/s3
B
cm2/s2/cm-1
k cm-1
2/5/1991 12:18 36.51 y.d.
C
height cm
epsilon cm2/s3
2/5/1991 12:18 36.51 y.d.
D
height cm
u* cm/s
2/5/1991 12:18 36.51 y.d.
E
height cm
Ubar cm/s

Fig. 6d

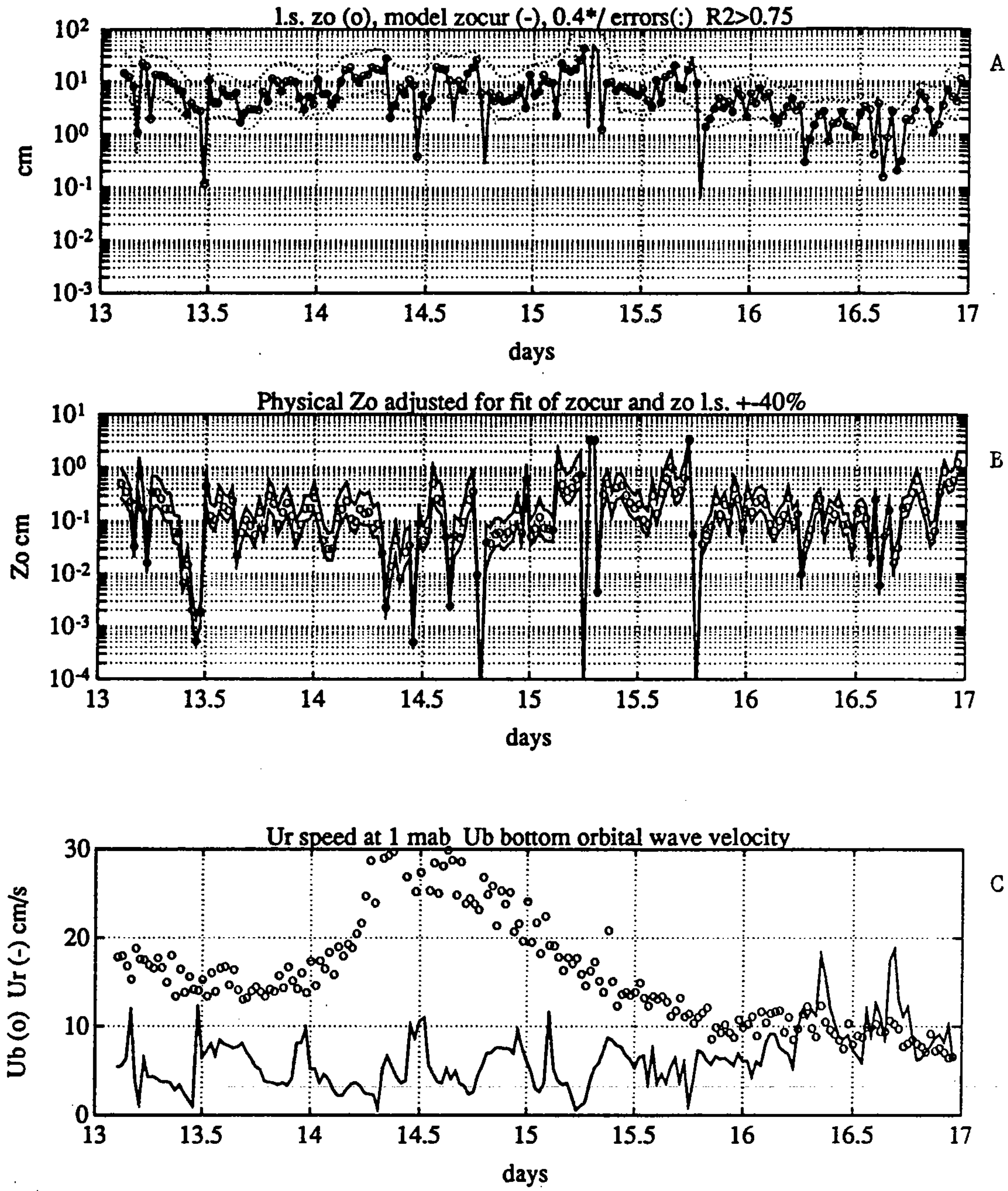
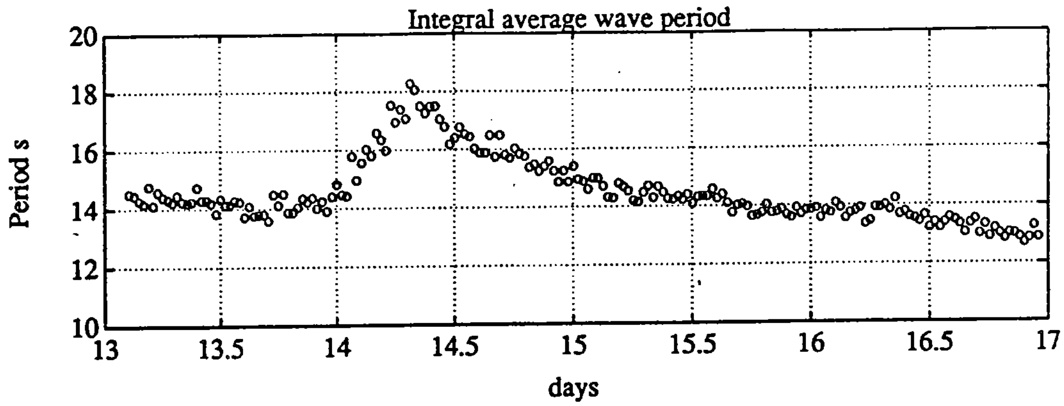


Fig. 7(*a-f*). Application of Grant and Madsen wave current model. Plot *A*: The least squares estimate of z_o used to match the model $z_{o_{cur}}$. Plot *B*: The physical z_o derived from the model. Plot *C*: The reference velocity, U_r, and wave orbital velocity, U_b. Plot *D*: The wave period. Plot *E*: The shear velocity from least squares and $u_{*_{cur}}$ from the model. These will agree quite closely when $z_{o_{cur}}$ and $z_{o_{1.s}}$ are matched. Plot *F*: The wave shear stress velocity scale, $u_{*_{wave}}$. The stress actually working on the bed. Plot *G*: The least squares regression coefficient.



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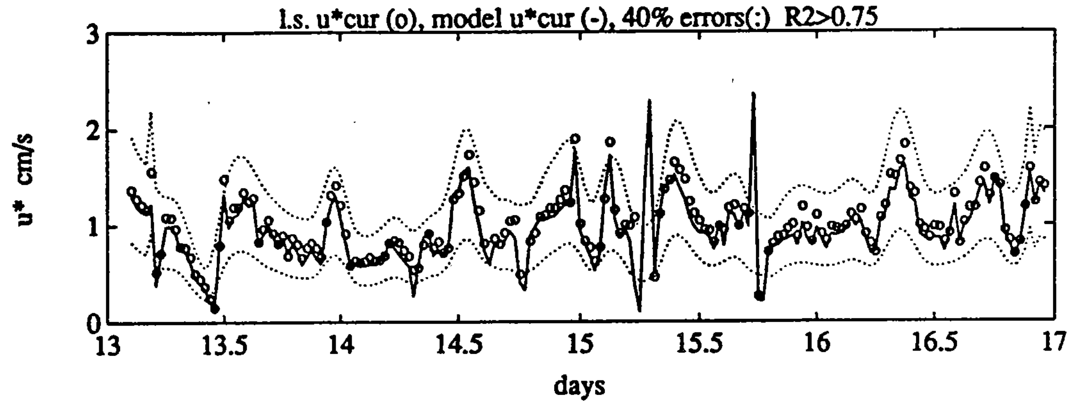
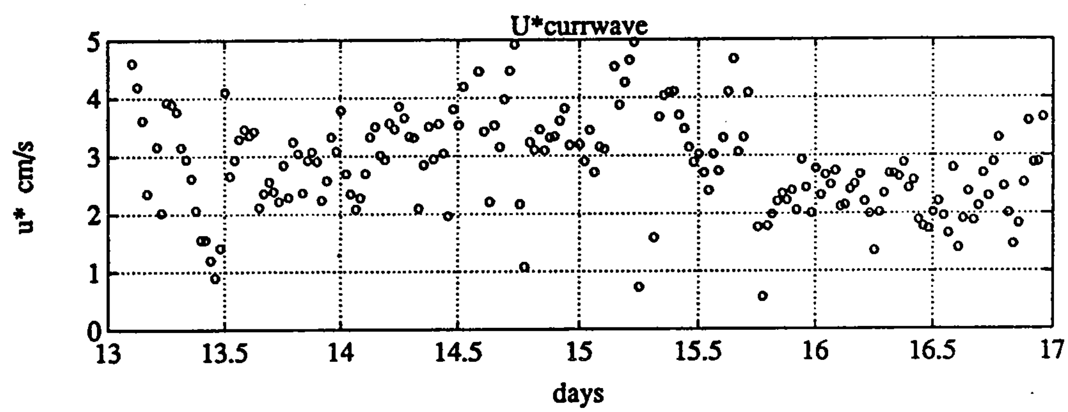
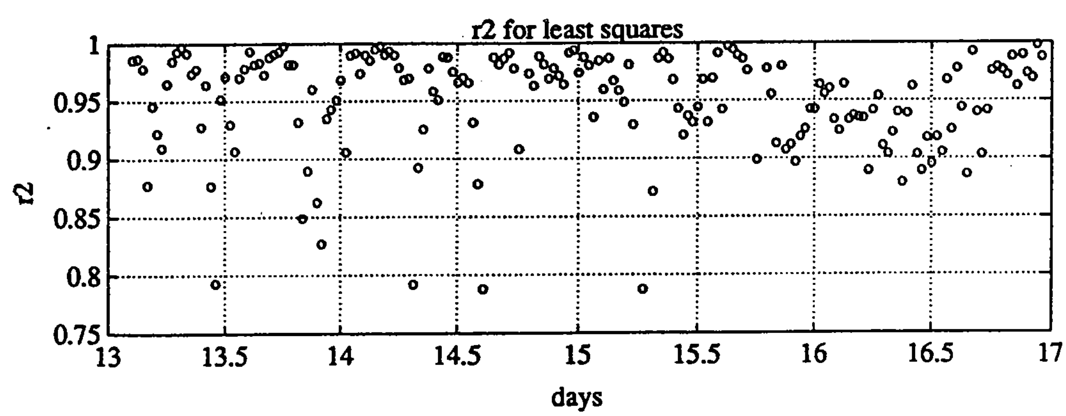


E



F



G

Fig. 7a (cont.)

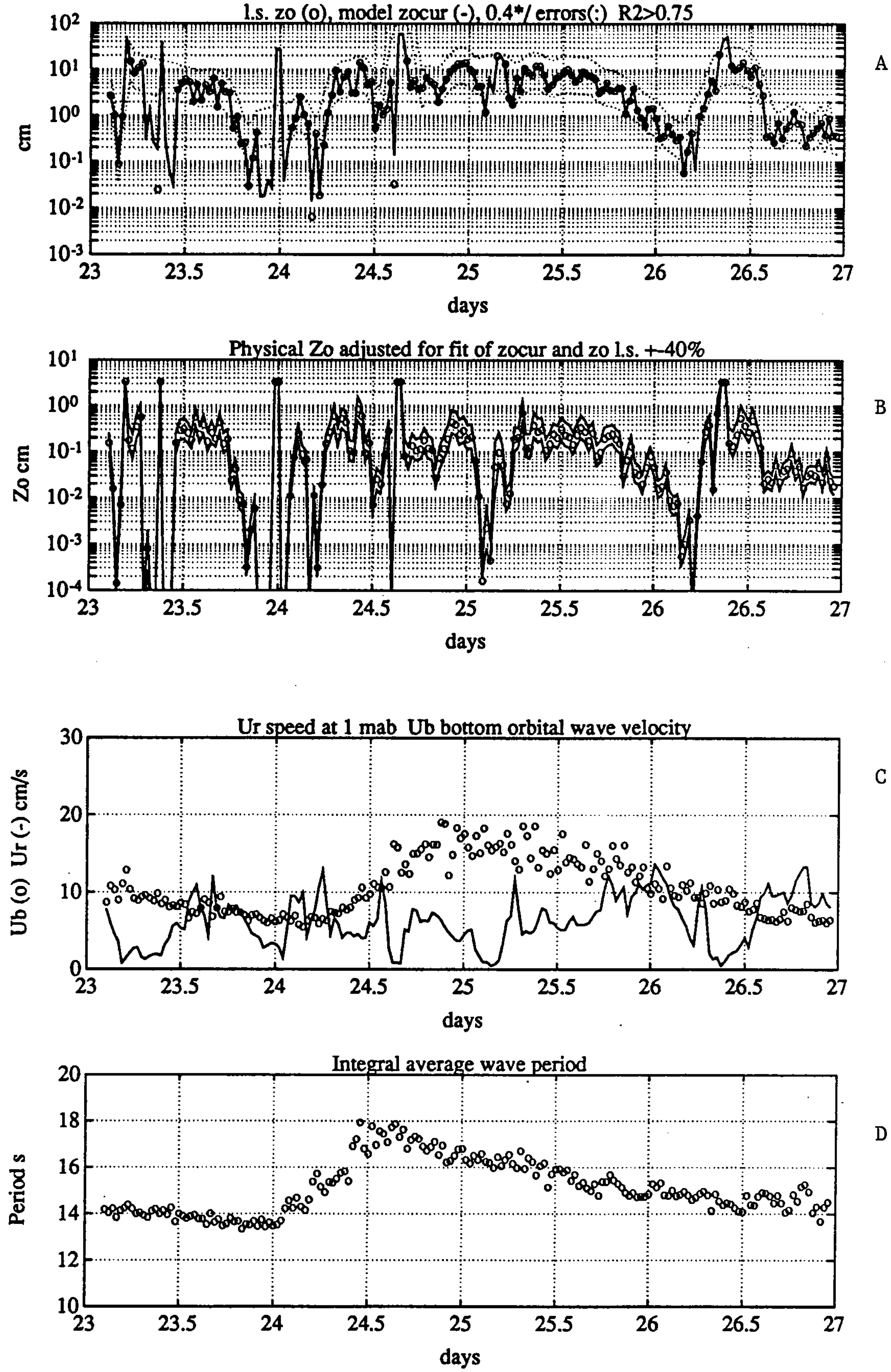
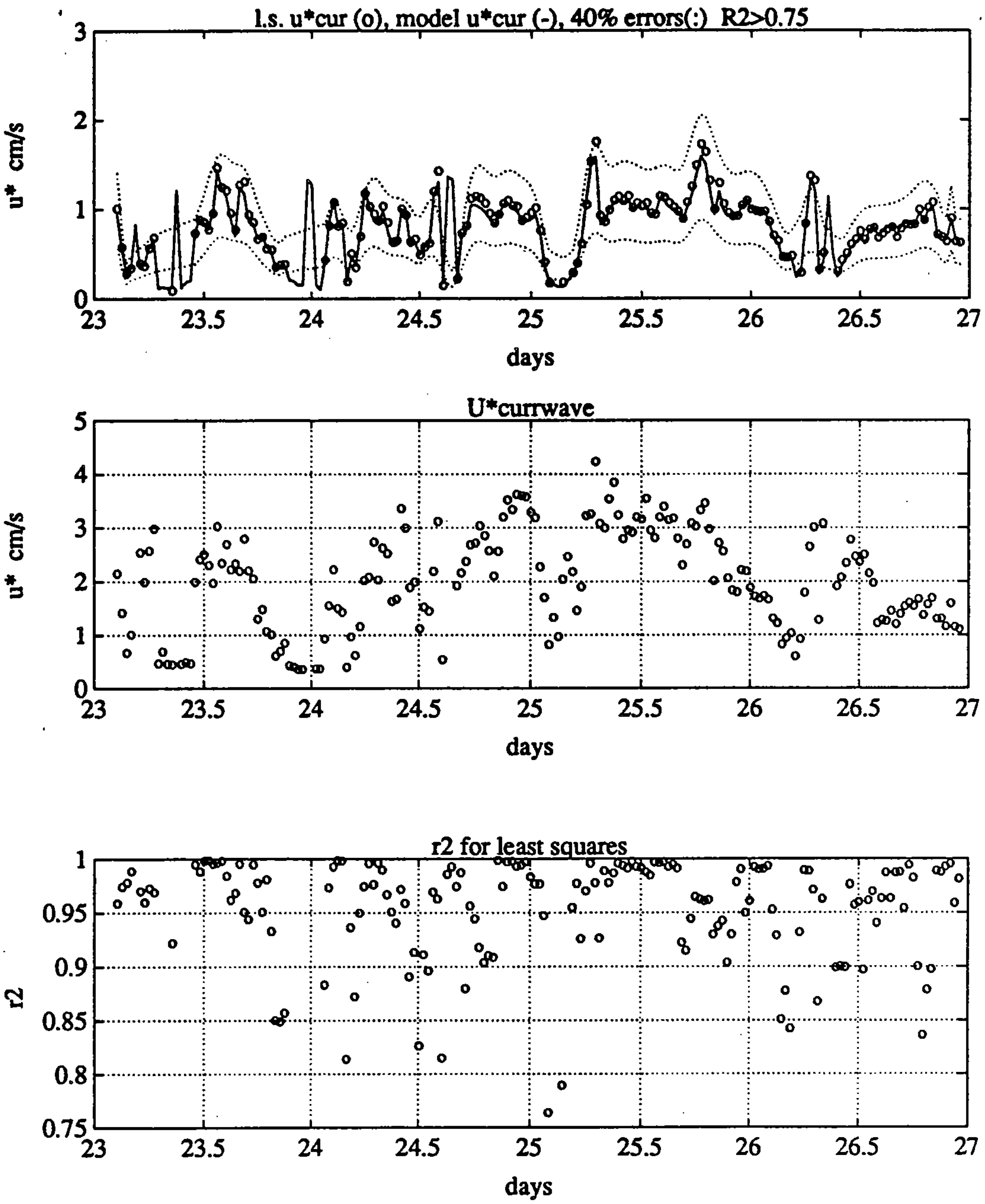

l.s. zo (o), model zocur (-), 0.4*/ errors(:) R2>0.75
cm
days
A
Physical Zo adjusted for fit of zocur and zo l.s. +-40%
Zo cm
days
B
Ur speed at 1 mab Ub bottom orbital wave velocity
Ub (o) Ur (-) cm/s
days
C
Integral average wave period
Period s
days
D

Fig. 7b



E

F

G

Fig. 7b (cont.)

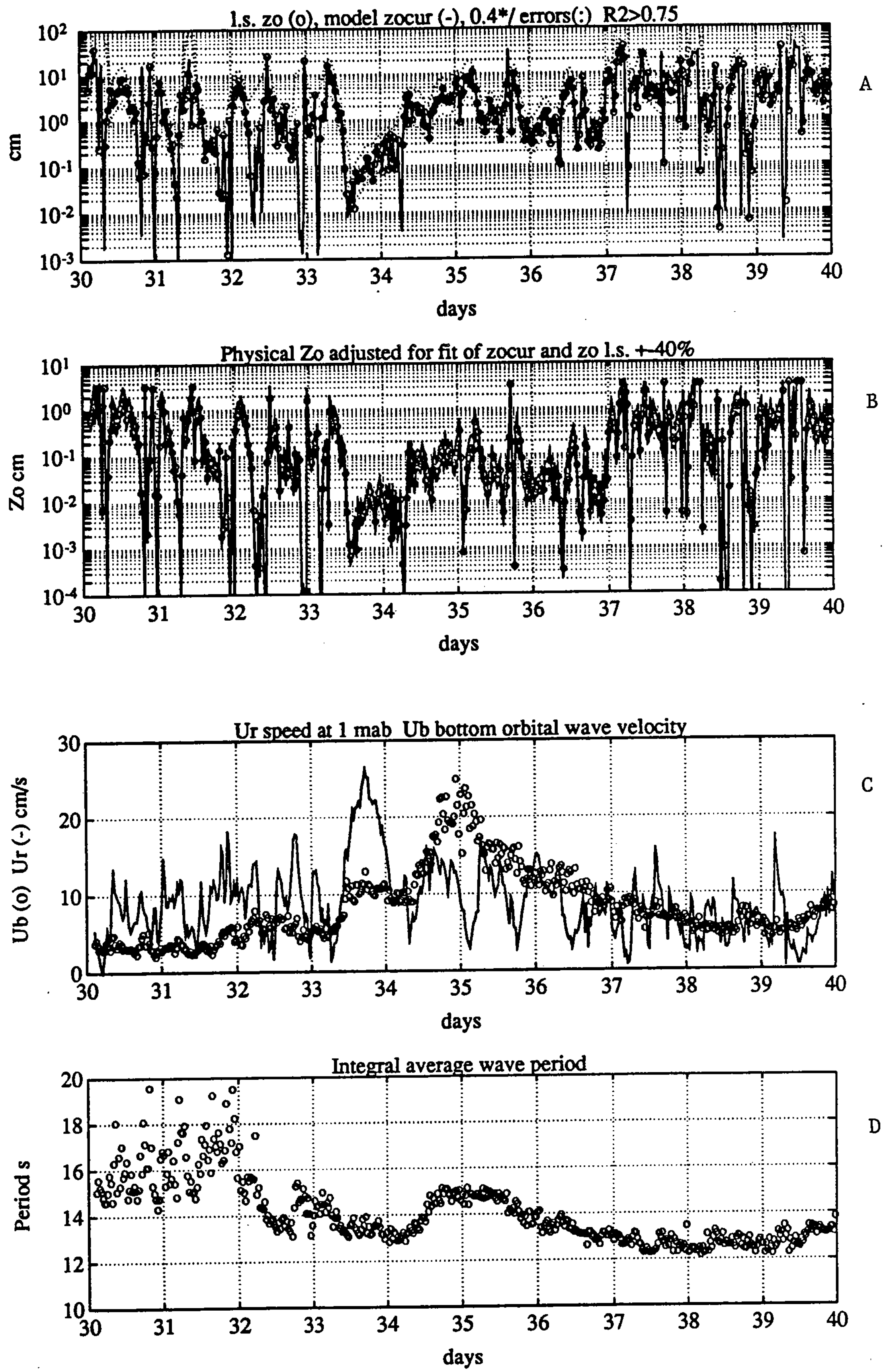

l.s. zo (o), model zocur (-), 0.4*/ errors(:) R2>0.75
cm
days
A
Physical Zo adjusted for fit of zocur and zo l.s. +-40%
Zo cm
days
B
Ur speed at 1 mab Ub bottom orbital wave velocity
Ub (o) Ur (-) cm/s
days
C
Integral average wave period
Period s
days
D

Fig. 7c

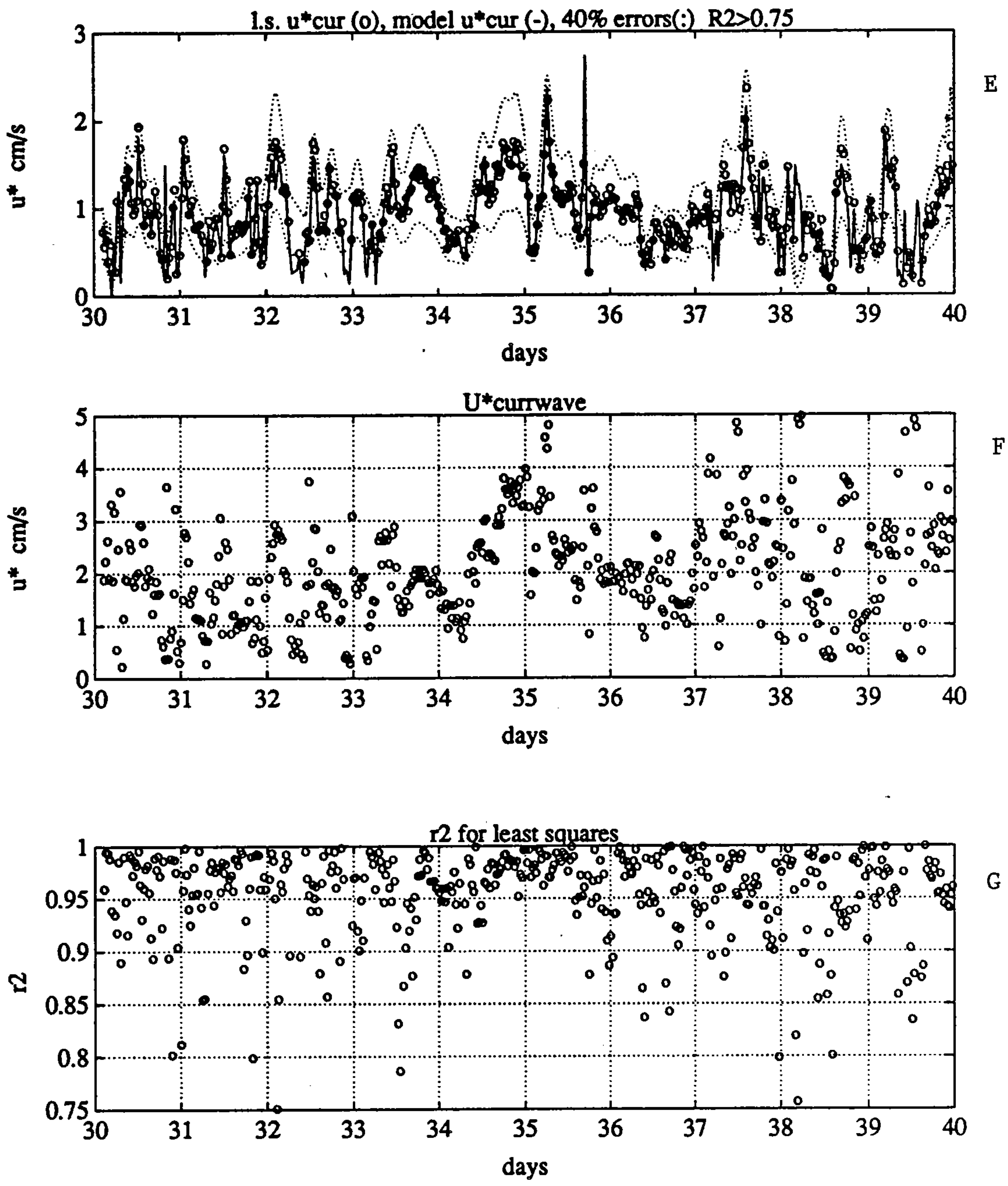

l.s. u*cur (o), model u*cur (-), 40% errors(:) R2>0.75
u* cm/s
days
E
U*currwave
u* cm/s
days
F
r2 for least squares
r2
days
G

Fig. 7c (cont.)

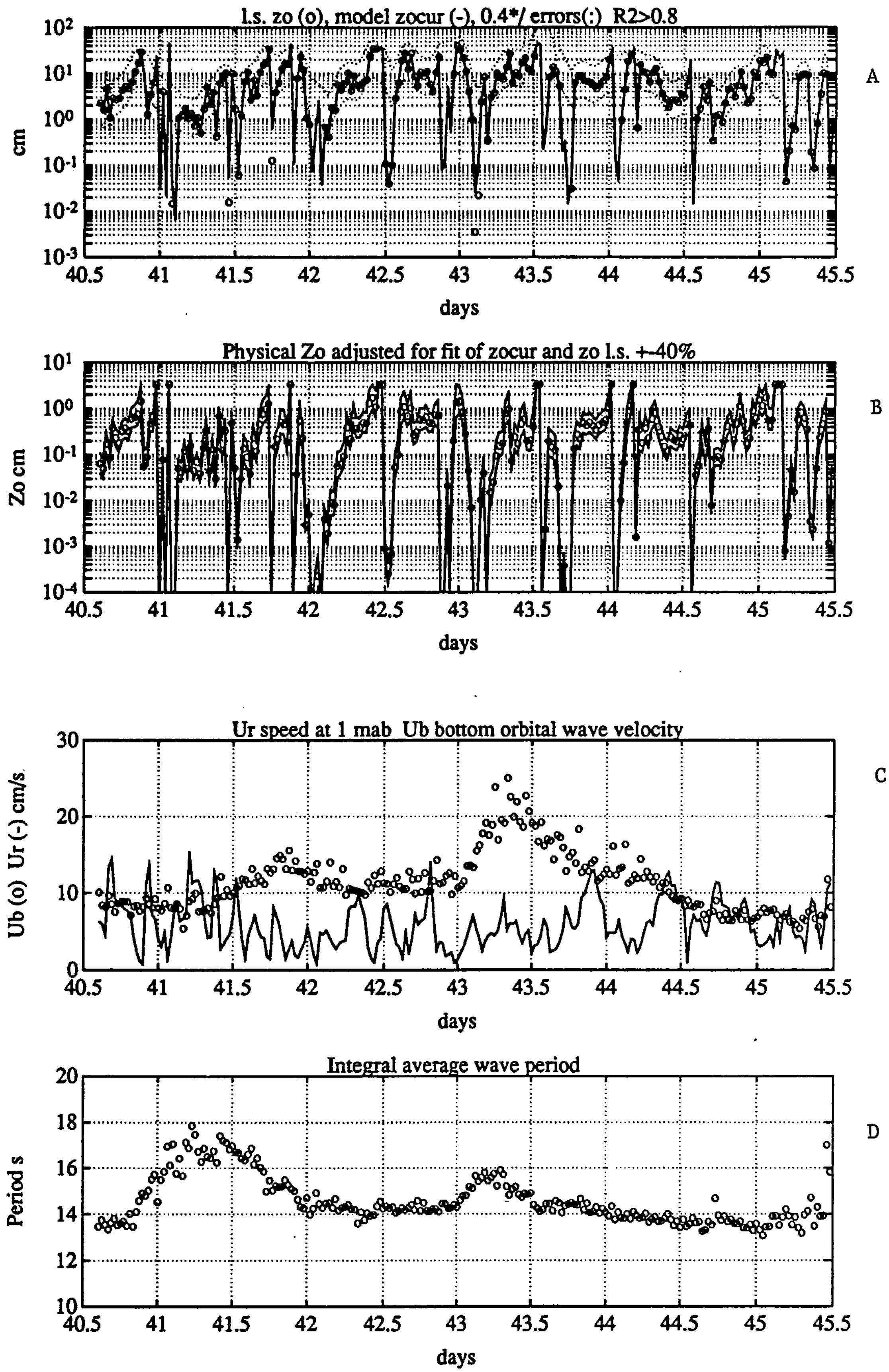

l.s. zo (o), model zocur (-), 0.4*/ errors(:) R2>0.8
cm
days
A
Physical Zo adjusted for fit of zocur and zo l.s. +-40%
Zo cm
days
B
Ur speed at 1 mab Ub bottom orbital wave velocity
Ub (o) Ur (-) cm/s
days
C
Integral average wave period
Period s
days
D

Fig. 7d

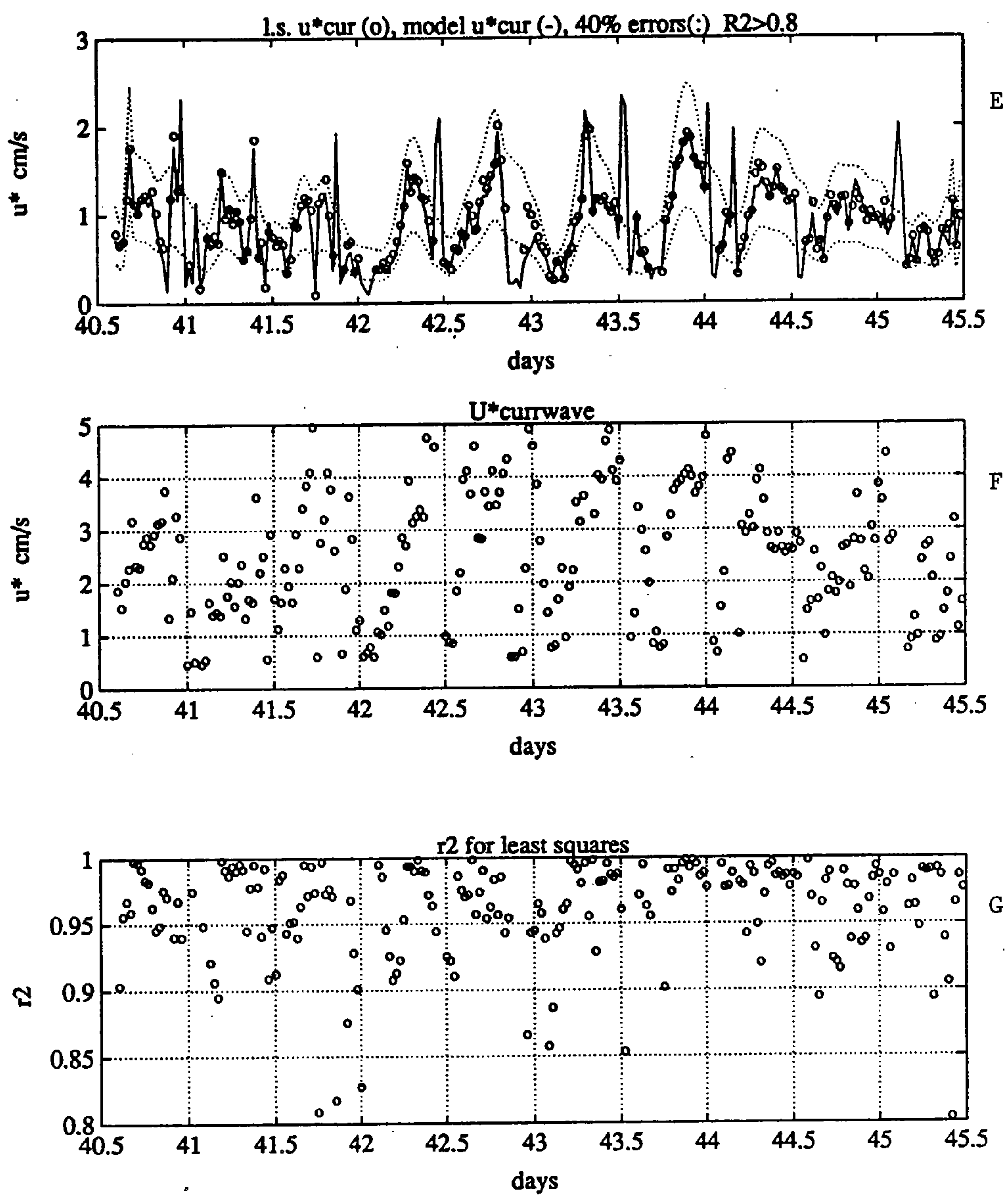

l.s. u*cur (o), model u*cur (-), 40% errors(:) R2>0.8
u* cm/s
days
E
U*currwave
u* cm/s
days
F
r2 for least squares
r2
days
G

Fig. 7d (cont.)

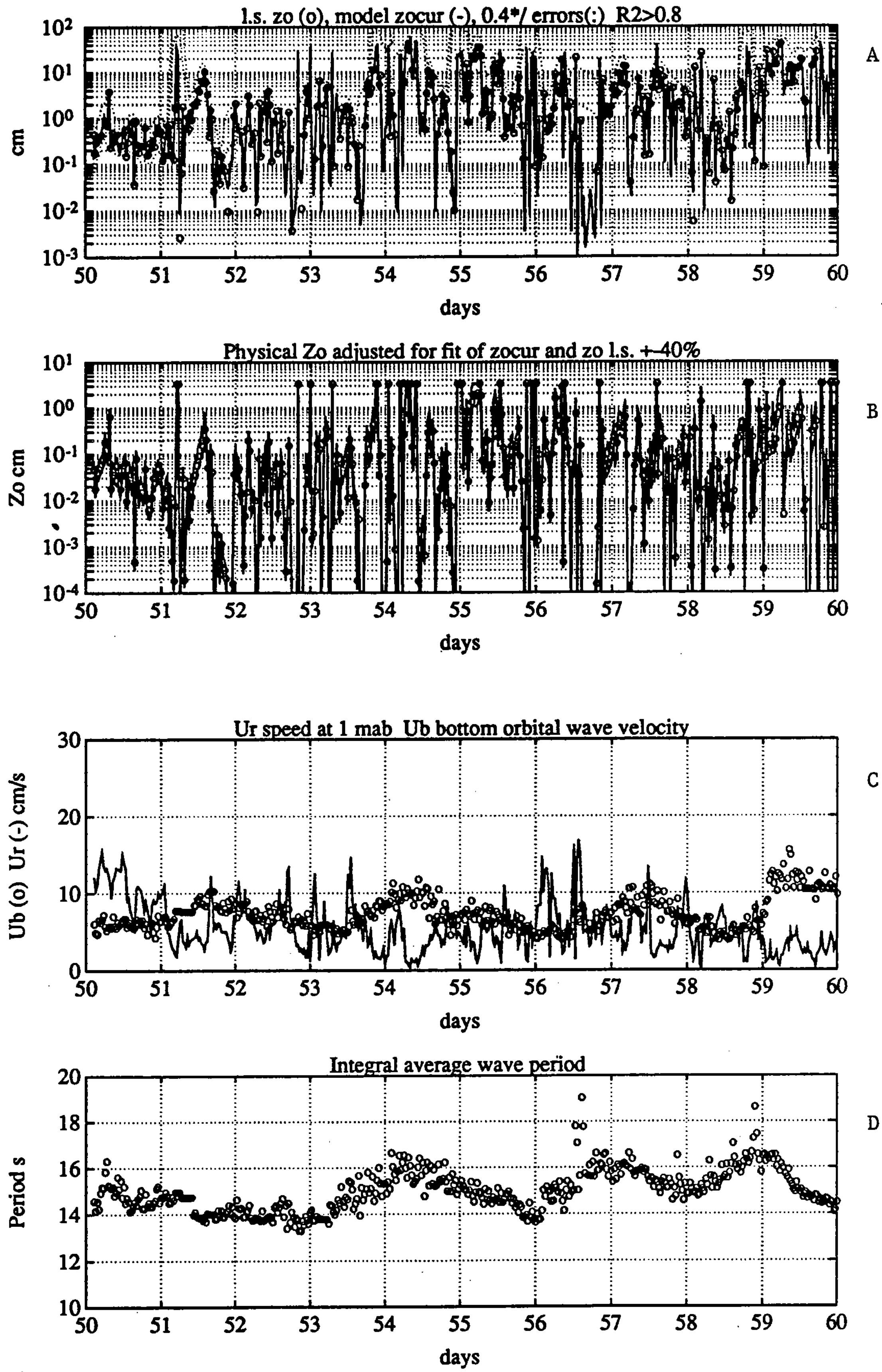
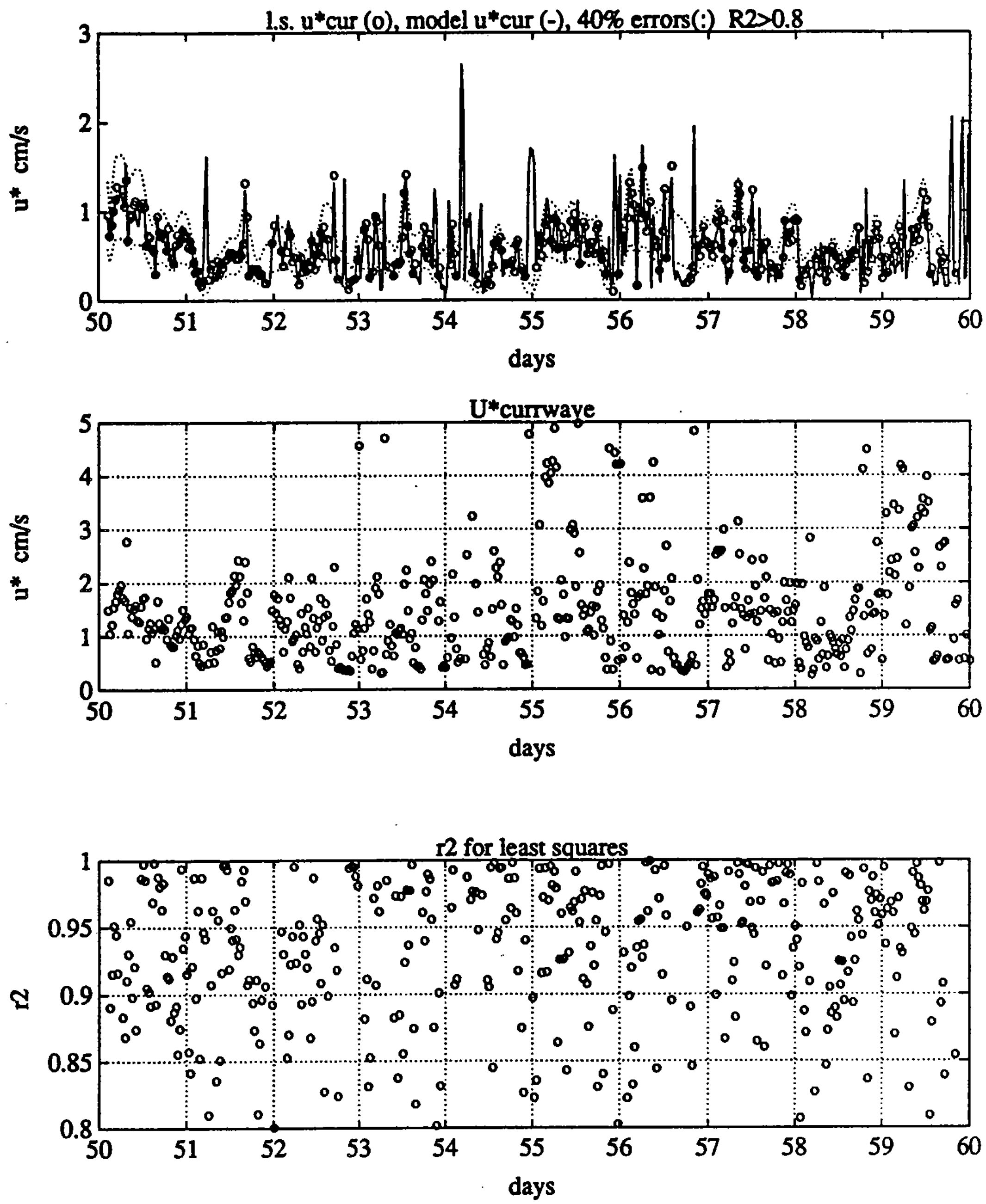

l.s. zo (o), model zocur (-), 0.4*/ errors(:) R2>0.8
cm
days
A
Physical Zo adjusted for fit of zocur and zo l.s. +-40%
Zo cm
days
B
Ur speed at 1 mab Ub bottom orbital wave velocity
Ub (o) Ur (-) cm/s
days
C
Integral average wave period
Period s
days
D

Fig. 7e



E

F

G

Fig. 7e (cont.)

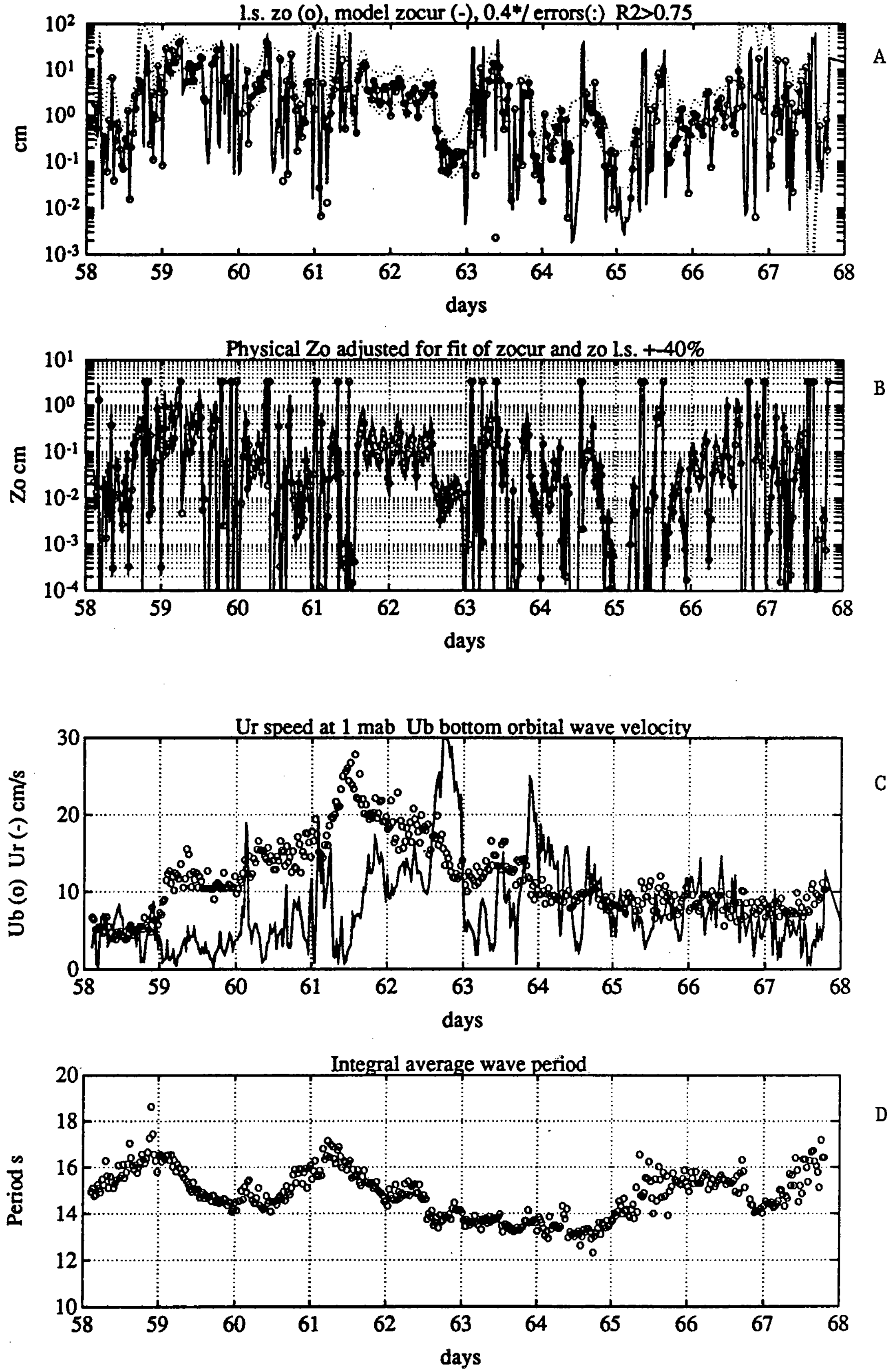

l.s. zo (o), model zocur (-), 0.4*/ errors(:) R2>0.75
cm
days
A
Physical Zo adjusted for fit of zocur and zo l.s. +-40%
Zo cm
days
B
Ur speed at 1 mab Ub bottom orbital wave velocity
Ub (o) Ur (-) cm/s
days
C
Integral average wave period
Period s
days
D

Fig. 7f

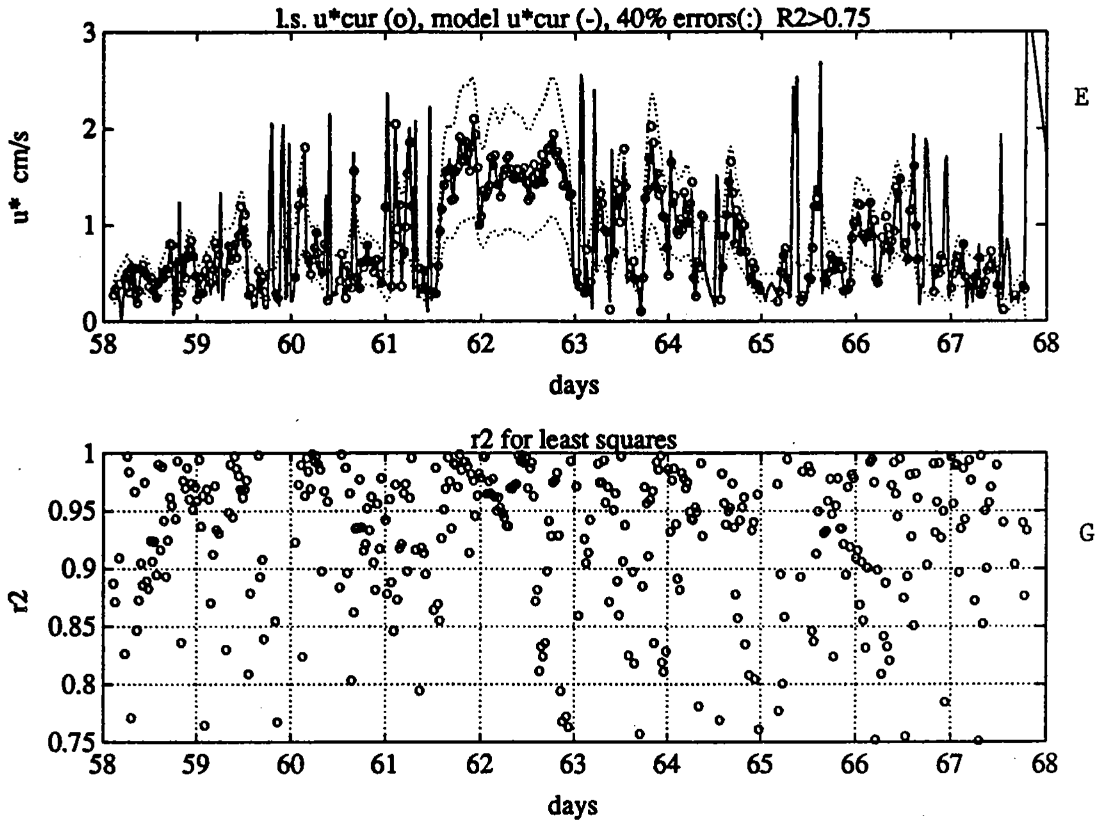

l.s. u*cur (o), model u*cur (-), 40% errors(:) R2>0.75
u* cm/s
days
E
r2 for least squares
r2
days
G

Fig. 7f (cont.)

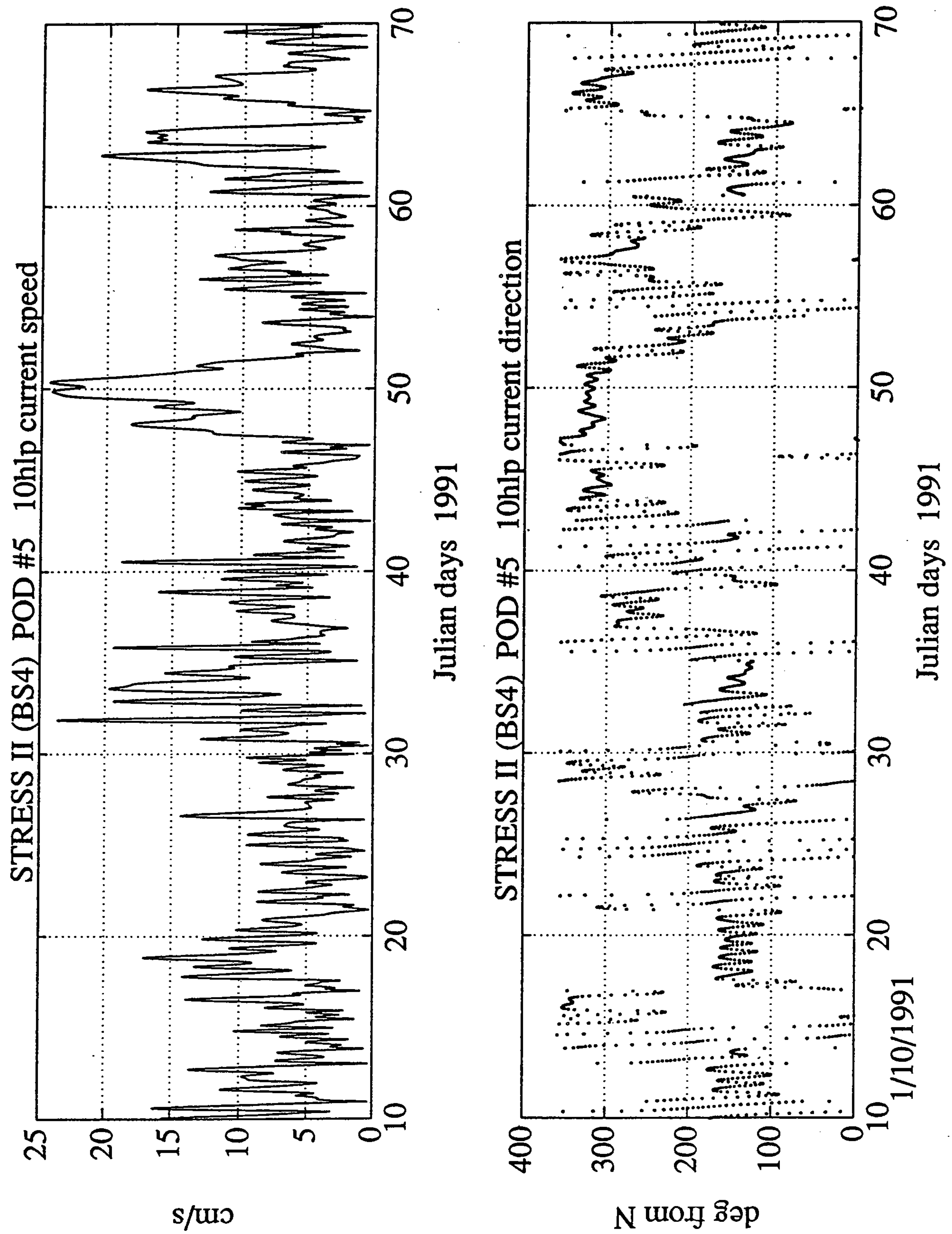


Fig. 8. Mean speed and direction for the fifth pod at 2.54 m.a.b. This data is 10 hour low passed.

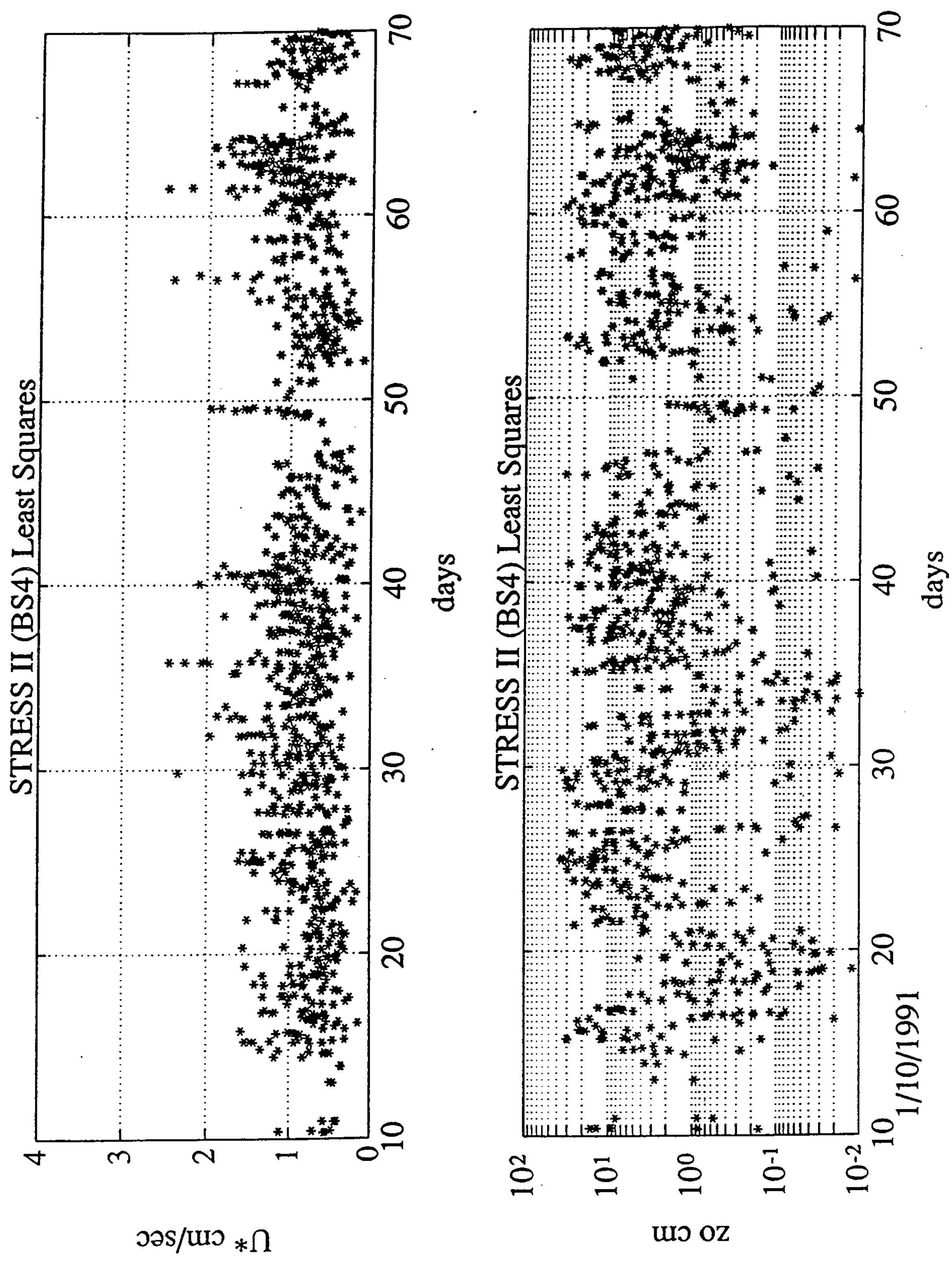


Fig. 9. Least squares estimates of the slope of the logarithmic velocity profile yield u_* and z_o. This plot shows only estimates for which R^2 is greater that 0.8.

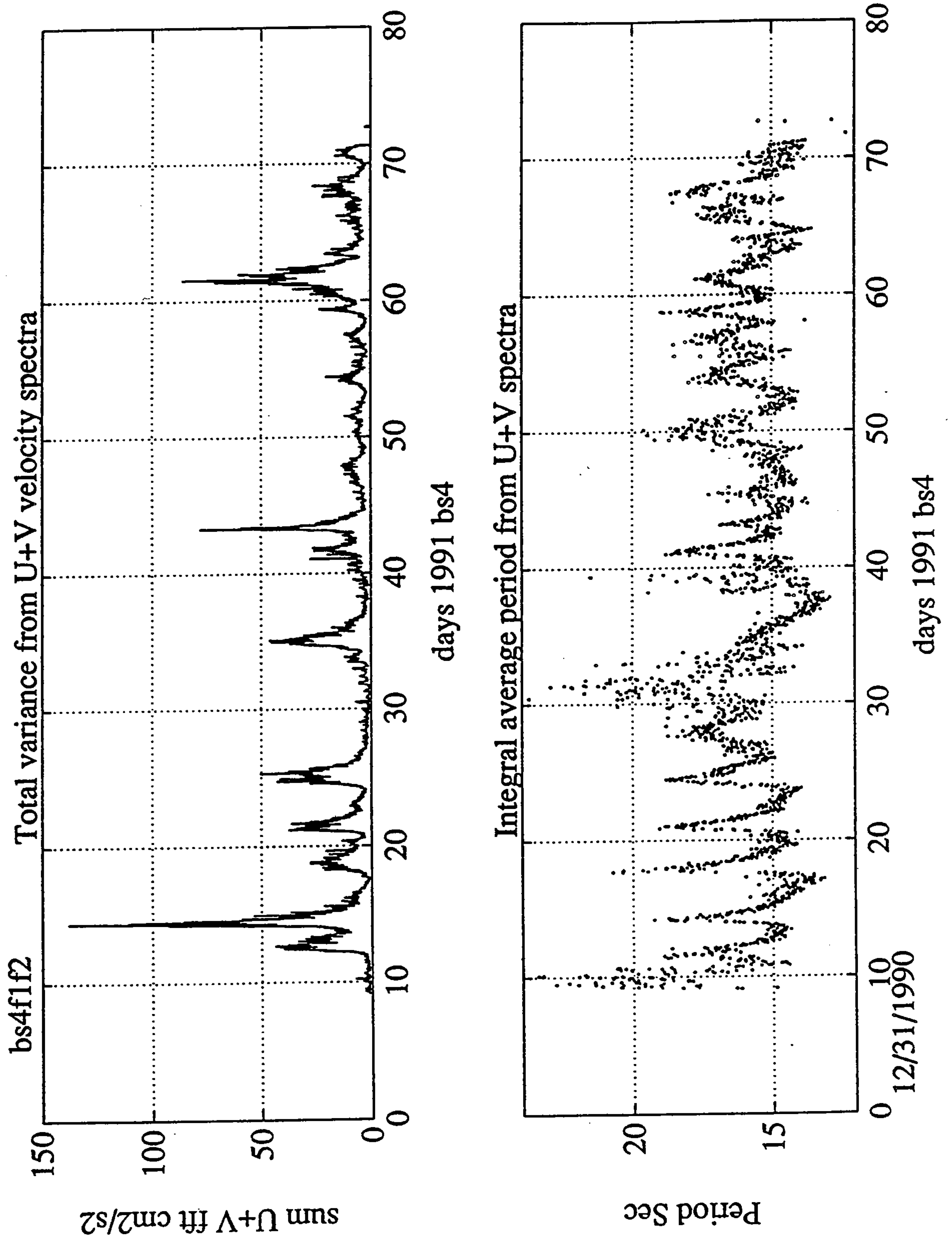
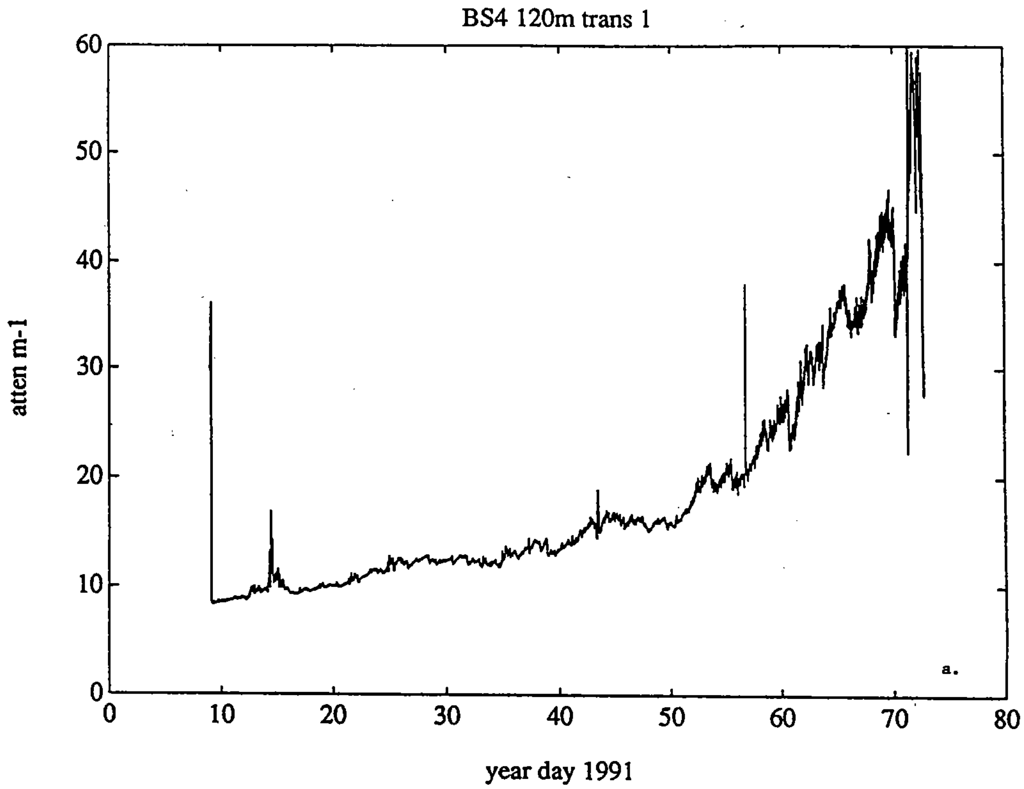


Fig. 10. Total velocity variance derived by summing the FFT estimates across frequencies 0.003255 to 0.1302 Hz. The period of the waves is estimated by spectral weighted averages of the frequency.



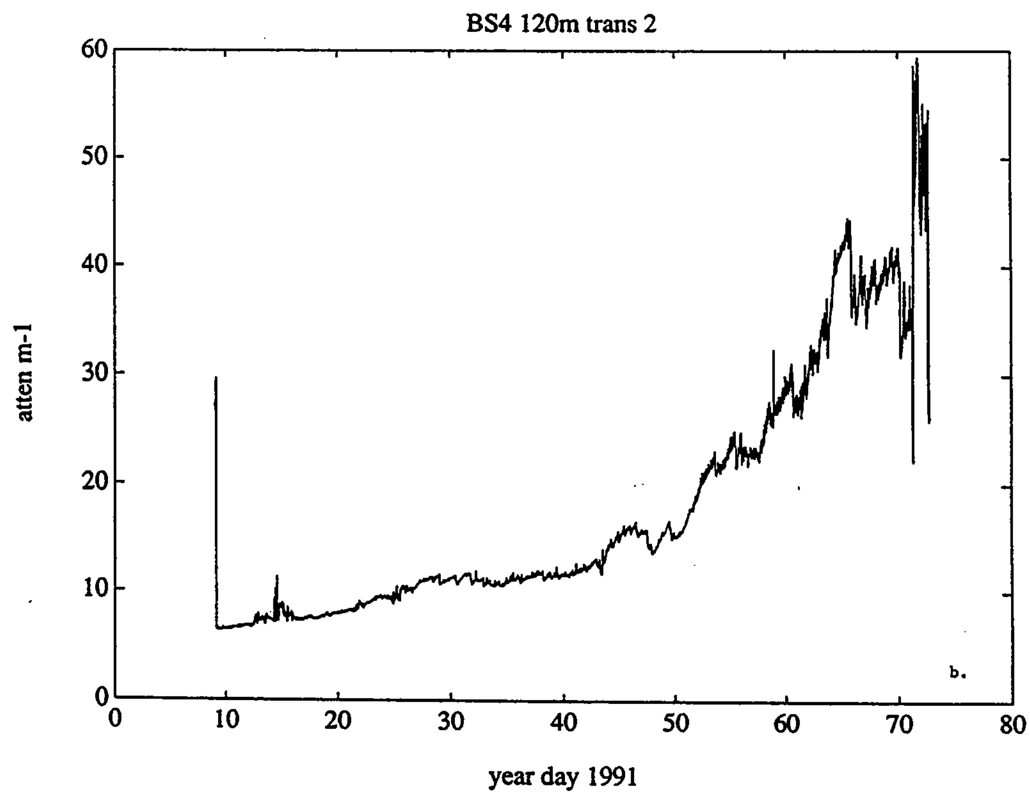


Fig. 11(*a, b*). Transmissometers 1(a) and 2(b). Considerable clouding or fouling of transmissometers through the deployment is evident.

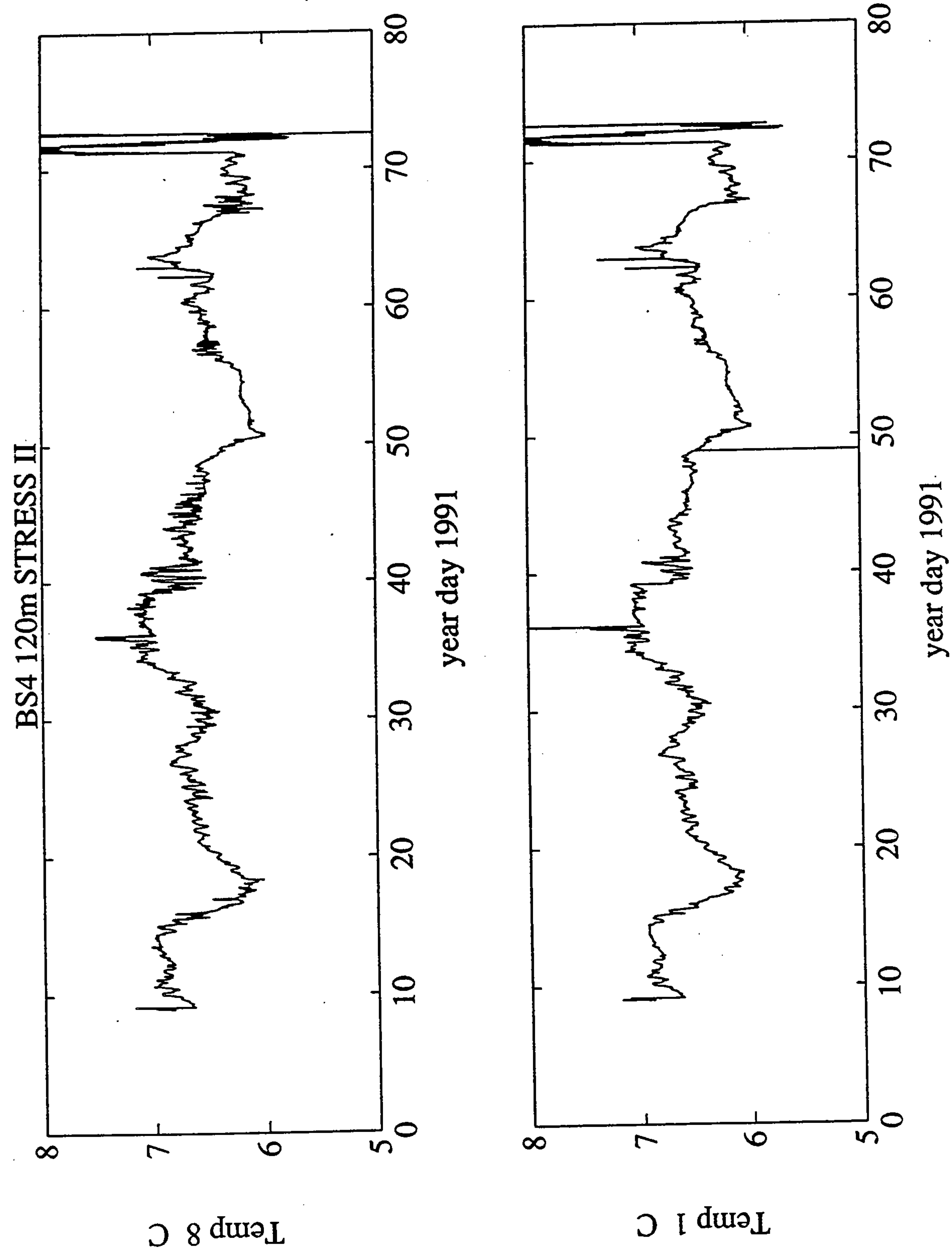


Fig. 12. Temperature records for the deployment. BS4 (120m depth) thermistors at position 8 (5.85 m.a.b.) and position 1 (0.21 m.a.b.).

Acknowledgements

The Sediment TRansport Events on Shelves and Slopes experiment was funded by the Geology and Geophysics Program and the Coastal Sciences Program of the Office of Naval Research under ONR Grants: N00014-89-J-1058 to the Woods Hole Oceanographic Institution and N00014-90-J-1046 to the Skidaway Institute of Oceanography. This support is gratefully acknowledged.

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16. Abstract (Limit: 200 words)

Two Benthic Acoustic Stress Sensor (BASS) equipped tripods were deployed in the Sediment TRansport Events on Shelves and Slopes (STRESS) experiment on the California Shelf acquiring data from January to March 1991. They measured velocity profiles in the bottom boundary layer over the lowest 5 meters. Transmissometers, thermistors, and a pressure sensor on each tripod provided suspended sediment concentration, stratification, and wave spectral information, as well.

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sediment transport
boundary layer stress

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

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